CRANFIELD UNIVERSITY

ROLANDO VEGA DÍAZ

ANALYSIS OF AN ELECTRIC ENVIRONMENTAL CONTROL SYSTEM TO REDUCE THE ENERGY CONSUMPTION OF FIXED-WING AND ROTARY-WING AIRCRAFT

SCHOOL OF ENGINEERING
MSc by research

MSc BY RESEARCH THESIS
Academic Year: 2010 - 2011

Supervisor: Dr Craig Lawson
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ABSTRACT

Nowadays the aviation industry is playing an important role in our daily life, since is the main medium that satisfies the present human needs to reach long distances in the fastest way. But such benefit doesn't come free of collateral consequences. It is estimated that each year, only the air transport industry produces 628 mega tonnes of CO_2. Therefore, urgently actions need to be implemented considering that the current commercial fleet will be doubled by 2050. The research field for more efficient aircraft systems is a very constructive field; where novel ideas can be exploited towards the mitigation of the coming air transport development.

In this research the configuration of the Environmental Control System (ECS) has been analysed aiming to reduce its energy consumption for both, fixed-wing and rotary-wing aircraft. This goal is expected to be achieved mainly through the replacement of the main source of power that supplies the ECS, from pneumatic to electric. Differently from the conventional ECS, a new electric-source technology is integrated in the system configuration to compare its effects on the energy consumption. This new technology doesn't bleed air directly from the engines; instead of that, it takes the air directly from the atmosphere through the implementation of an electric compressor. This new technology has been implemented by Boeing in one of its most recent airplanes, the B787.

Towards achieving the main goal, a framework integrated with five steps has been designed. An algorithmic analysis is integrated on the framework. The first step meets the required aircraft characteristics for the analysis. The second step is in charge of meeting the mission profile characteristics where the overall analysis will be carried out. The third step assesses the conventional ECS penalties. The fourth step carries out a complex analysis for the proposed electric ECS model, from its design up to its penalties assessment. The fifth step compares the analysis results for both, the conventional and the electric models.

The fourth step of the framework, which analyses the electric ECS, is considered the most critic one; therefore is divided in three main tasks. Firstly, a small parametric study is done to select an optimum configuration. This task is carried out towards meeting the ECS air conditioning requirements of a selected aircraft.

Secondly, the cabin temperature and pressurization are simulated to analyse the response of the configured electric ECS for a mission profile. And finally, the fuel penalties are assessed in terms of system weight, drag and fuel due power-off take.

To achieve the framework results, a model which receives the name ELENA has been created using the tool Simulink®. This model contains 5 interconnected modules; each one reads a series of inputs to perform calculations and exchange information with other modules.

Keywords:

Environmental Control System, Fixed-Wing, Rotary-Wing, Energy, Fuel Penalty, Mission, Air Conditioning, Pressurization, Thermal Balance.

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NOTATIONS

1. ABREVIATIONS

		Units (International System)
AMSL	Above the Mean Sea Level	m
AMSL	Above the Mean Sea Level	
AUM	All Up Mass	kg
AUM	All Up Mass	kg
ATM	Atmosphere	
BPR	Bypass Ratio	
cab	Cabin	
ETA	Combustion Efficiency	
C	Compressor	
CECS	Conventional Environmental Control System	
CFR	Cooling mass flow ratio	-
CFR	Cooling Mass Flow Ratio	
DOC	Direct Operational Cost	
EECS	Electric Environmental Control System	
EM	Electric Motor	
EPW	Electric Power	W
ECS	Environmental Control System	
ELENA	Environmental Control System Analysis Tool	
FAR	Fuel air ratio	-
FDM	Fuel Design Mass	kg
FW	Fuel flow	kg/s

FHV	Fuel heating value	J/kg
fus	Fuselage	
hx	Heat Exchanger	
in	Inlet parameter	
ISA	International Standard Atmosphere	
Ma	Mach number	
mf	Manifold	
max	Maximum	
PW	Net Shaft Power	W
FN	Net Thrust	N
EN	Number of engines	
EN	Number of engines	
PAX	Number of passengers	
out	Outlet parameter	
PDV	Pressure reduction valve	
PRV	Pressure release valve	
SPW	Shaft Power	W
SRI	Solar Radiation Index	-
SFC	Specific Fuel Consumption	kg/(N·s)
T	Turbine	

2. LIST OF SYMBOLS

		Units (International System)
h	Altitude	m
A	Area	m^2
ρ	Density	kg/m^3
D	Drag	N
η	Efficiency	-
γ	Gamma	-
g	Gravity	m/s^2
q_c	Heat by convection	W
q_{sr}	Heat by sun radiation	W
q_G	Heat generated in inside the system	W
τ	Heat transfer coefficient	$W/(m^2 \cdot K)$
R	Ideal gas constant	J/(kg·K) or J/(K·mol)
E	Internal energy	J
L	Lift	N
r	Lift to Drag Ratio	
Ma	Mach number	-
m	Mass	kg
$\dot{m}$	Mass flow/Pneumatic Power	kg/s
M	Molar mass	kg/mol
ε	Pressure drop	-
π	Pressure ratio	-
π	Pressure Ratio	-
σ_{sr}	Radiation intensity by the sun	W/m^2
d	Range/distance	m
f_s	Security factor	-
ϕ_{SFC}	SFC increase/decrease ratio	-
C_P	Specific Heat	J/(kg·K)
c	Speed of Sound	m/s
P	Static pressure	Pa
T	Temperature	K or °C
t	Time	s

t	Time	sec
Q	Total heat	W
v	Velocity/Speed	m/s
vs	Vertical speed	m/s
V	Volume	m^3
W	Weight	N

CHAPTER 1 | INTRODUCTION

1.1. The research for less-energy consuming systems

Nowadays the environmental impact produced by the air transportation industry has been a matter of big concern; according with [1]Clean Sky JTI (Joint Technology Initiative) it represents 2% of human-induced CO_2 emissions and 12% of the overall transport systems. This impact is reflected by the 628 mega tonnes of CO_2 produced yearly. Urgently strategies need to be implemented since it is estimated that the commercial fleet will be doubled by 2050 due to the introduction of about 1300 new international airports. Such strategies can be implemented with the research on less-energy consumer technologies in the aircraft systems. This is a field where novel ideas can be exploited to mitigate the coming collateral effects of the air transport industry.

1.2. The Environmental Control System

The Environmental Control System (ECS) is the responsible to provide a conditioned cabin for the crew and passengers on modern aircraft. This system must achieve requirements of pressure, temperature and air quality; especially in high altitudes where those aircraft perform its missions and where the conditions are too adverse for the human survival.

Considering study purposes, a conventional ECS is principally integrated with four sections; the air or pneumatic energy sources, the air conditioning pack, the cabin and the control unit. The following figure has been drawn to show the scheme for a fixed-wing aircraft. Other components like filters, intakes and ozone reduction packs are included in the ECS conditioning pack. Since such components don’t represent a considerable impact for the final comparison result, currently are not considered for this research.

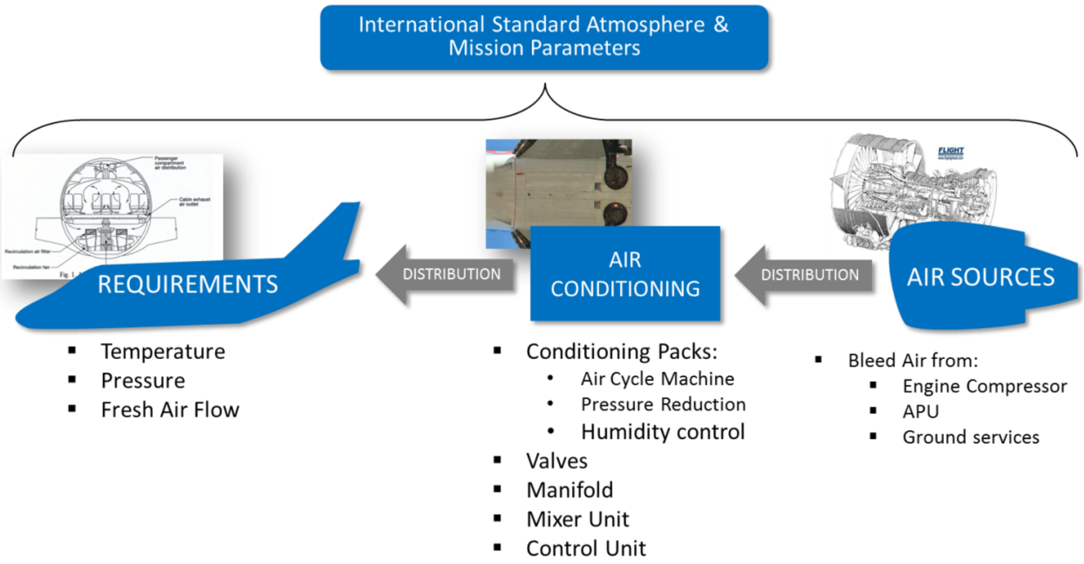


Figure 1: Common ECS scheme for fixed-wing aircraft

As seen on the previous figure, the pneumatic energy source provides the flow with an internal energy, which can be measured in terms of mass flow for thermal balance calculations. This mass flow is associated with their respective temperature, pressure and density. Depending on the kind of pneumatic source and the mission status, the mass flow can be provided with different characteristics. The pneumatic energy can be provided from engine bleeding, an Alternate Power Unit APU or simply form ground services when the aircraft is parked at the airport.

1.3. Aim and objective

Following the strategies to mitigate the environmental impact, a research is outlined for the energy consumption of the Environmental Control System (ECS). The ECS is the most energy-demanding system in the aircraft, consuming up to [2]75% of the energy designated for the aircraft systems and the 3-5% of the power produced by the engines. The importance in analysing the energy consumption of the ECS, allow us to improve the efficiency of the entire system altering their configuration, hence resulting on a reduction of the energy requirement for the aircraft and consequently for their emissions.

Is expected that the application of an electric ECS will achieve positive values on the reduction of the fuel penalty; since the process of bleeding air involves a considerable quantity of energy lose. This energy lose is represented with the reduction on the engine mass flow available; pressure drops through the ECS pipelines and temperature lose through the overall system.

1.4. Methodology

Aiming to achieve the main goal, the main source of power that supplies the ECS is replaced, from pneumatic to electric. Differently from the conventional ECS, a new electric-source technology is integrated in the system configuration to compare its effects on the energy consumption. This new technology doesn't bleed air directly from the engines; instead of that, it takes the air directly from the atmosphere through the implementation of an electric compressor. This new technology has been implemented by Boeing in one of its most recent airplanes, the B787.

In addition, to achieve the main goal a framework integrated with five steps has been designed. An algorithmic analysis is integrated on the framework. The first step meets the required aircraft characteristics for the analysis. The second step is in charge of meeting the mission profile characteristics where the overall analysis will be carried out; this mission profile includes the three main flight phases, climbing, cruise and a descent. The third step assesses the conventional ECS fuel penalties. The fourth step carries out a complex analysis for the proposed electric ECS model. The fifth step compares the analysis results for both, the conventional and the electric models. The framework algorithm is shown in the following figure.

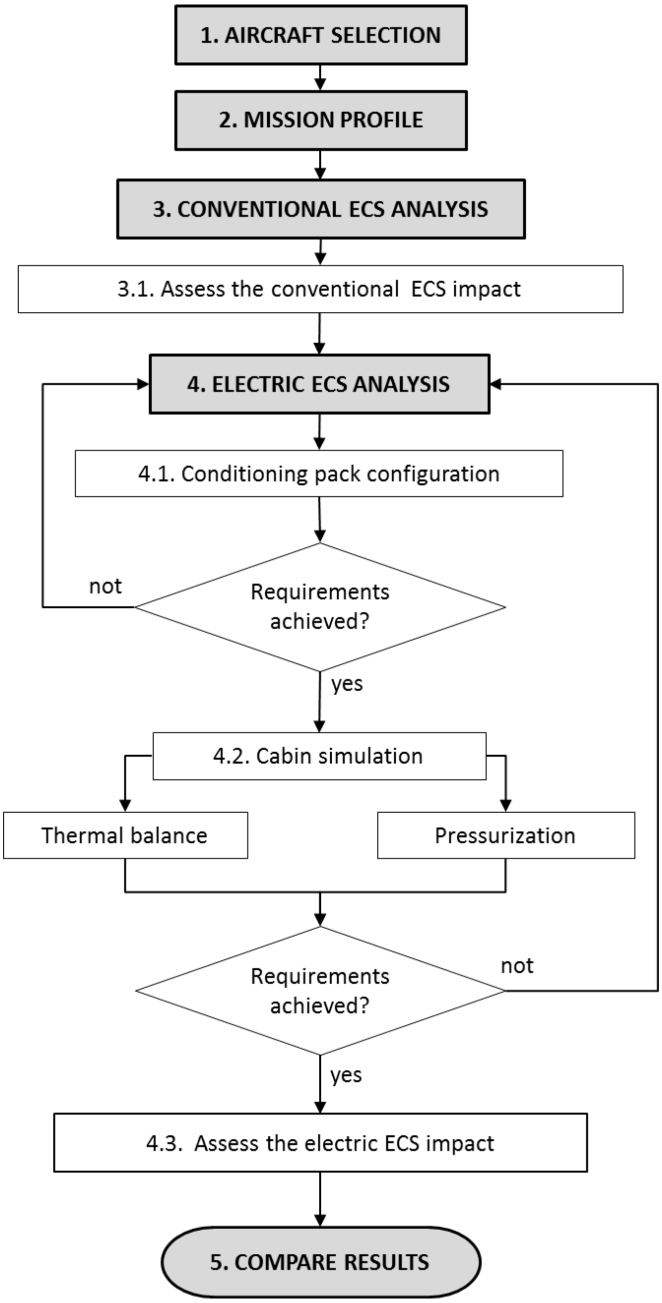


Figure 2: Framework flowchart

The fourth step of the framework, which analyses the electric ECS, is considered the most complex; therefore is divided in three main tasks. Firstly, a small parametric study to select an optimum configuration is made. This task is carried out towards meeting the ECS air conditioning requirements of a selected aircraft. Secondly, the cabin temperature and pressurization are simulated to analyse the response of the configured electric ECS for this mission profile; this simulation lets conclude if the new proposed ECS configuration achieves the cabin requirements for this mission profile. And finally, the fuel penalties are assessed in terms of fuel flow due power-off take, system drag generated and system weight.

To achieve the framework results, a model which receives the name ELENA has been created using the tool Simulink®. This model contains 5 interconnected modules; each one reads a series of inputs to perform calculations and exchange information with other modules. The name ELENA has been selected as an acronym for Environmental Control System Analysis Tool.

The main analysis is performed for both, fixed-wing and rotary-wing aircraft, though a contribution for two areas of a project from Clean Sky JTI (Joint Technology Initiative); that belongs to the European Commission for funding research on Europe. The fixed-wing analysis is part of the area “Technology Evaluator” and the rotary-wing analysis is part of the area “Systems for Green Operation”.

1.5. Thesis Scheme

The chapter one gives a general overview of the research, giving an introduction about the research justification, the main objective and the proposed methodology. The second chapter presents the main concepts which were acquired with the literature review. Chapter three presents the implemented methodology with the design of the frame work and the design of the simulation tool ELENA. Chapter four and five present the results for fixed-wing aircraft; each chapter is focused on a different aircraft. Chapter five presents the results for the rotary-wing aircraft. Chapter six presents the conclusions. The seventh chapter presents recommendations for future work related with this research.

CHAPTER 2 | THE ENVIRONMENTAL CONTROL SYSTEM

2.1. The ECS Principles

Nowadays with the increasing demand on the modern commercial air transportation—jet-propelled, high speed and very manoeuvred aircraft—it has been very essential to maintain a conformable cabin for the passengers in all the phases of any flight mission. This job can only be done by the [3]Environmental Control System (ECS), which combines the principles of thermodynamics and fluid dynamics to achieve its goal. However it is not easy to maintain desire air cabin requirements, since any flight mission involves various phases, each one with a particular atmospheric condition.

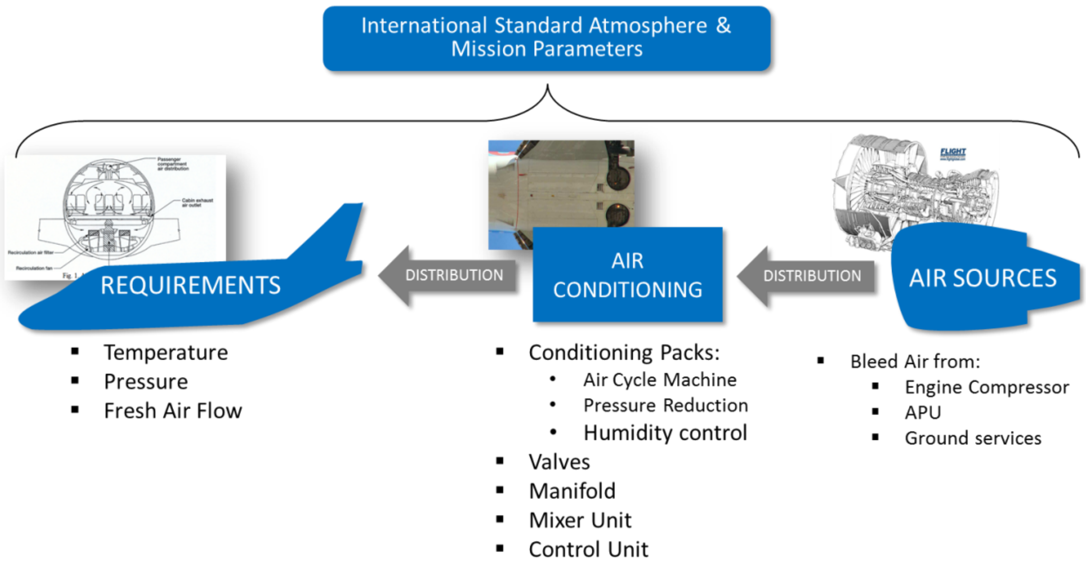


Figure 3: Common ECS scheme for fixed-wing aircraft

Considering study purposes, a conventional ECS is principally integrated with four sections; the air or pneumatic energy sources, the air conditioning pack, the cabin and the control unit. The previous figure has been drawn to show the scheme for a fixed-wing aircraft. Other [4]components like filters, intakes and ozone reduction packs are included in the ECS conditioning pack. Since such components don't represent a considerable impact for the final comparison result, currently are not considered for this research.

As seen on the previous figure, the pneumatic energy source provides the flow with an internal energy, which can be measured in terms of mass flow for thermal balance calculations. This mass flow is associated with their respective temperature, pressure and density. Depending on the kind of pneumatic source and the mission status, the mass flow can be provided with different characteristics. This pneumatic energy can be provided from engine bleeding, an Alternate Power Unit APU or simply form ground services when the aircraft is parked at the airport. The following figure has been drawn to show the distribution of pneumatic power from its sources.

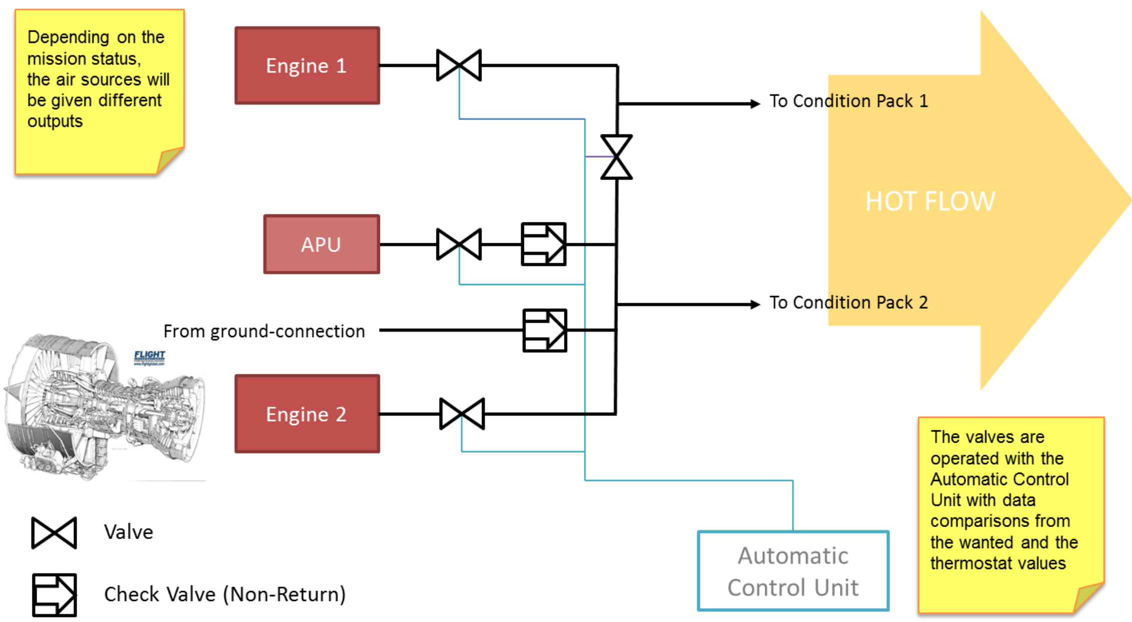


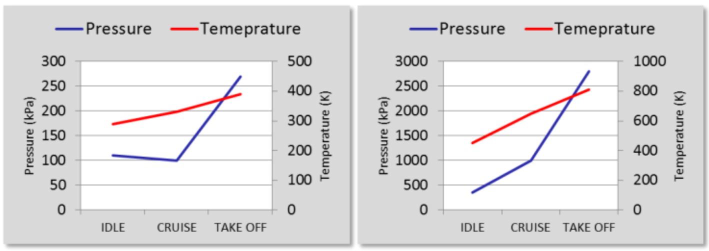
Figure 4: ECS air sources distribution

The main parameters that are considered for the engine sources are the mass flow, temperature and pressure. Those parameters change depending on the flight stage.

Figure 5: Pneumatic energy outputs

The following [4]figure has been drawn to show some typical values of pressure and temperature provided by aircraft engines at the three flight stages, idle, cruise and take-off.

	IPC		HPC	
	P(kPa)	T(K)	Pa(kPa)	T(K)
IDLE	110	290	350	450
CRUISE	100	330	1000	650
TAKE OFF	270	390	2800	810



*Values taken from Aircraft System, Ian Moir and Allan Seabridge

Figure 6: Engine bleed flow pressure and temperature at various flight stages

The air conditioning section transforms the internal energy of this flow, which have high pressure and temperature, to provide an appropriate air flow for the passengers. This component works with components such as pressure reduction valves, heat exchangers and conditioning packs. The following figure has been drawn to show the flow distribution for the conditioning packs.

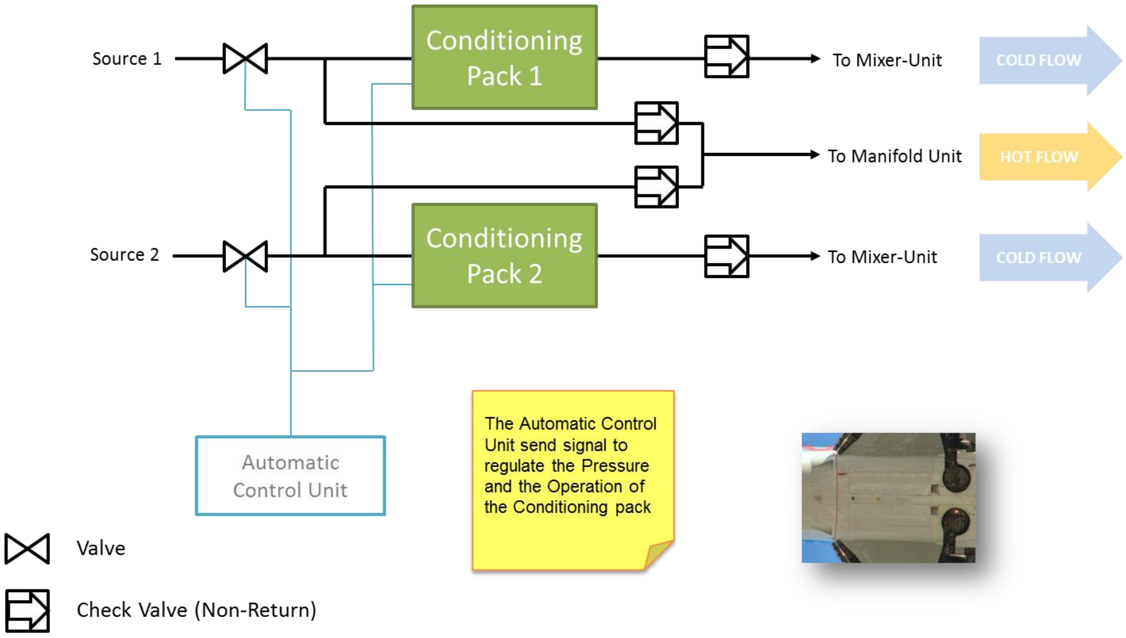


Figure 7: ECS air conditioning section

The cabin establishes the quantity of energy required; hence, it is affected by its volume and heat loads.

The control unit regulates the entire air conditioning following the normal operational requirements. That unit sends signals to regulate automatically the pressure and with reduction valves and the temperature with the operation of valves located in the manifold. The pressurization is regulated as well with the action of a Pressure Release Valve. The following figure has been drawn to show the function of the control unit.

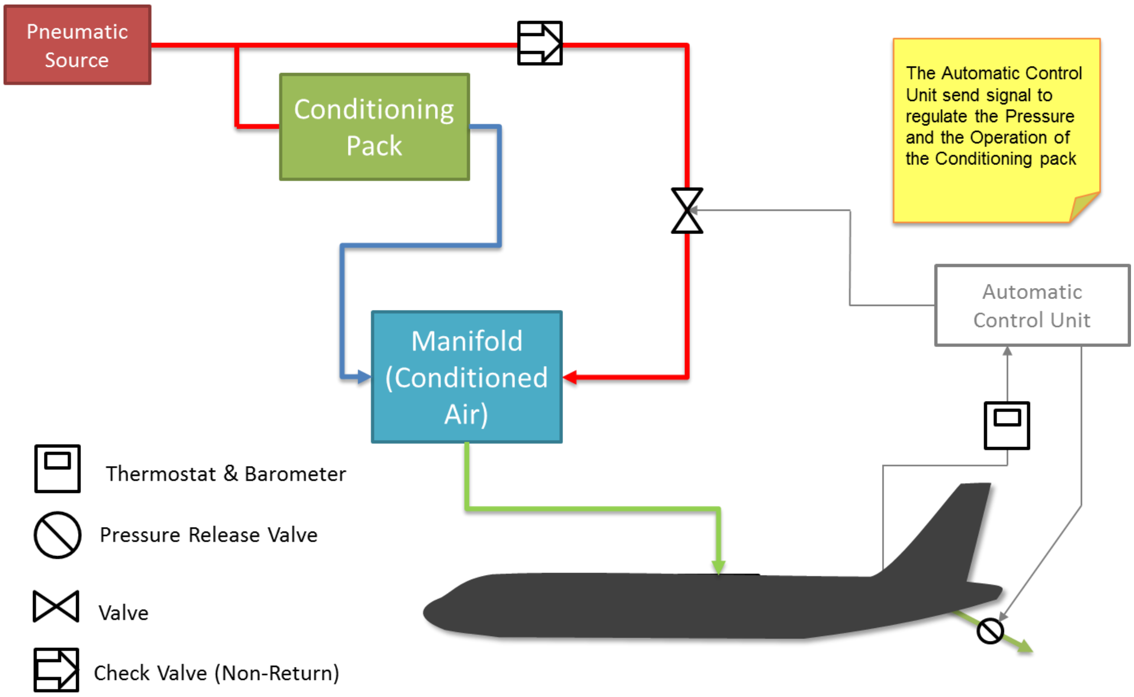


Figure 8: Basic ECS scheme with the control unit

Depending on the aircraft manufacturer, the control unit has basic manual controls to adjust the ECS operation. For normal scheduled flights, those controls are mainly used to control the temperature for the cabin sections and the cockpit. The following figure shows a control unit which is located in the aircraft cockpit.

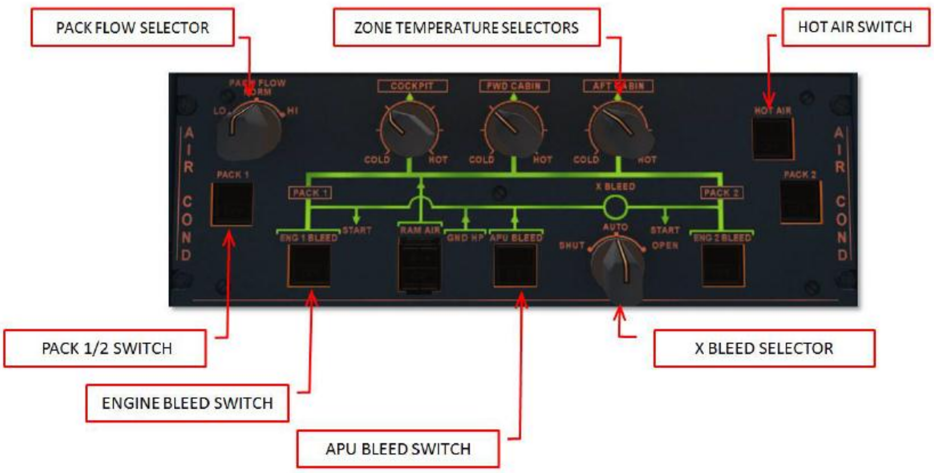


Figure 9: ECS cockpit control unit

2.2. Air Conditioning Configurations

The ECS provides a confortable cabin for the passengers instead of the adverse ambient conditions which can be present during a flight mission. However to aim its objective, various [5]configurations in the conditioning section can be selected depending on the customer requirements. Those configurations include the Air Cycle Machine, the Vapour Cycle Machine, the Combustion Heater and the Exhaust Gases Heater. The following table shows the capabilities of each system.

Conditioning pack	Capability
Air Cycle Machine	Cooling and heating
Vapour Cycle Machine	Cooling
Combustion Heater	Heating
Exhaust Gases Heater	Heating

The Air Cycle Machine, in spite of consuming more energy and produce more payload penalty, offers both capabilities which makes it the most common conditioning pack used in aviation. This component works with the principle of transforming heat into work.

The Vapour Cycle Machine is light weighted, but can’t afford big demands for big commercial airplanes and only is capable to provide cooling, also is efficient in a 60%. This component works with a HCFC refrigerant, dropping the temperature of a system volume by removing heat and sending it elsewhere.

The Combustion Heater only provides heating; their advantages are presented with its low fuel consumption. This system works heating fresh air flow through a heat exchanger that receives heat from a combustion chamber; this process uses the convection principle of the thermodynamics. Since this conditioning pack only heats atmospheric air, is not suitable for pressurized cabins or non-pressurized cabins that require cooling.

The [6]exhaust gases heater only provides heating. This conditioning pack works though a heat exchanger that transfer the heat produced by the exhaust gases to fresh air taken from the atmosphere; is commonly presented on light trainee aircraft. The major disadvantage is the risk of mixture with exhaust gases if a rupture is presented in the system distribution.

In the case of the fixed-wing aircraft the most common configuration is the Air Cycle Machine; therefore will be considered for this research. In the other hand for the rotary-wing aircraft the selection was more complex. Therefore, a survey was done to determinate the common ECS conditioning packs. The following condition, civil helicopters registered in the United Kingdom with more than 20 units, was used as constrain for this survey. The next table shows the results.

CIVIL HELICOPTERS IN THE UNITED KINGDOM (MORE THAN 20 UNITS)		
Helicopter	ECS	Seats
Augusta A109	Optional Bleed Air Heater and Environmental Control Unit	8
Bell 47 (Piston)	Not mentioned	3
Bell 206 Jet Ranger	Optional ECS and Heater	5
Enstrom F28/280 (Piston)	Cabin Heated and Ventilated	3
Eurocpter 350 Ecureuil	Cabin air conditioned optional	6
Eurocpter 355 Ecureuil 2	Not mentioned	6
Eurocopter AS 332 Super Puma	Cabin and flight deck Heated and Ventilated	Up to 29
Eurocopter BO105	Heating System Optional	6
MD500	Aero Engineering Corporation air conditioning system or Fargo pod-mounted air conditioner optional	5
Robinson R22 (Piston)	Cabin Heated and Ventilated	2
Robinson R44 (Piston)	Heating and ventilation	4
Schweizer 300C (Piston)	Exhaust muff heating and ventilation kit available	3
Sikorsky S-61	Not mentioned	30
Sikorsky S-76	Optional air conditioning	15

Table 1: Most common helicopters registered in the United Kingdom

Seeking at [7]Jane's references, the ECS is optional for civil helicopters. For heating purposes, a combustion heater or direct hot bleed air is used; and for cooling purposes an air cycle/vapour machine is used. The selection of the ECS depends on the costumer requirement regarding the operation purpose. For this research the Air Cycle Machine and the Combustion Heater will be analysed; placing more emphasis in the first one. The next figure has been drawn to show the conventional ECS scheme for rotary-wing.

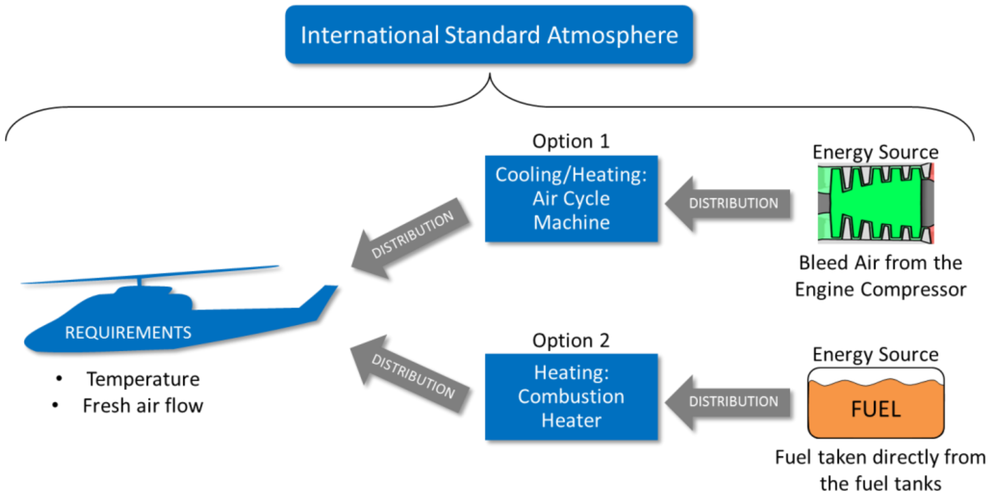


Figure 10: Common ECS scheme for rotary-wing aircraft

2.3. Air Cycle Machine Principles

For cooling purposes an Air Cycle Machine is analysed, following the previous analysis made in the sub-chapter 2.2. The following figures have been drawn to show the principle of the Air Cycle Machine.

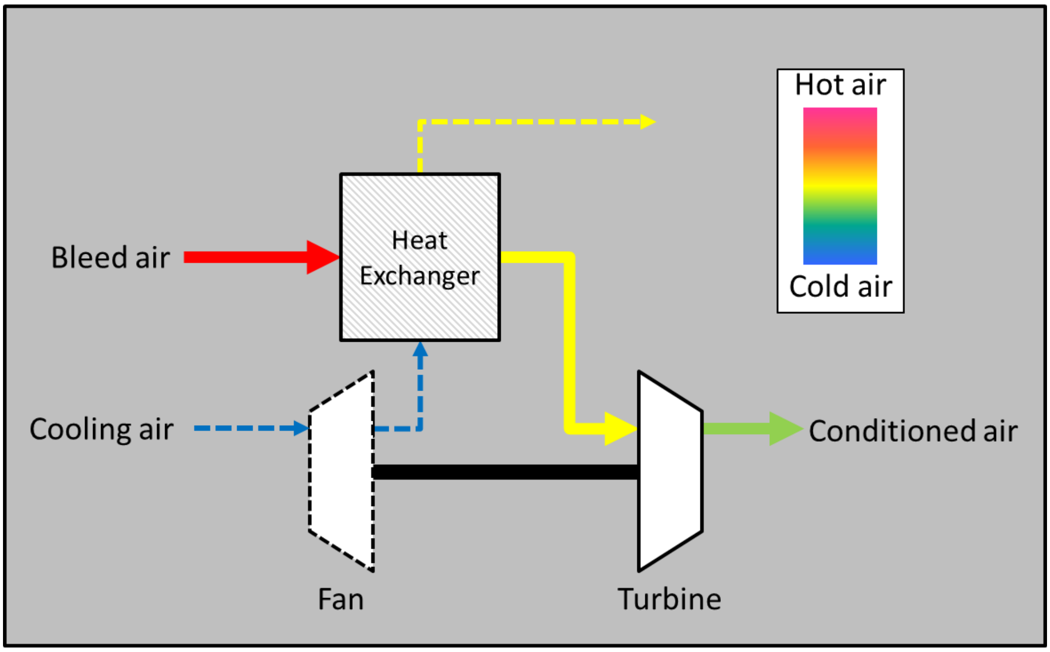


Figure 11: Air Cycle Machine - Turbofan

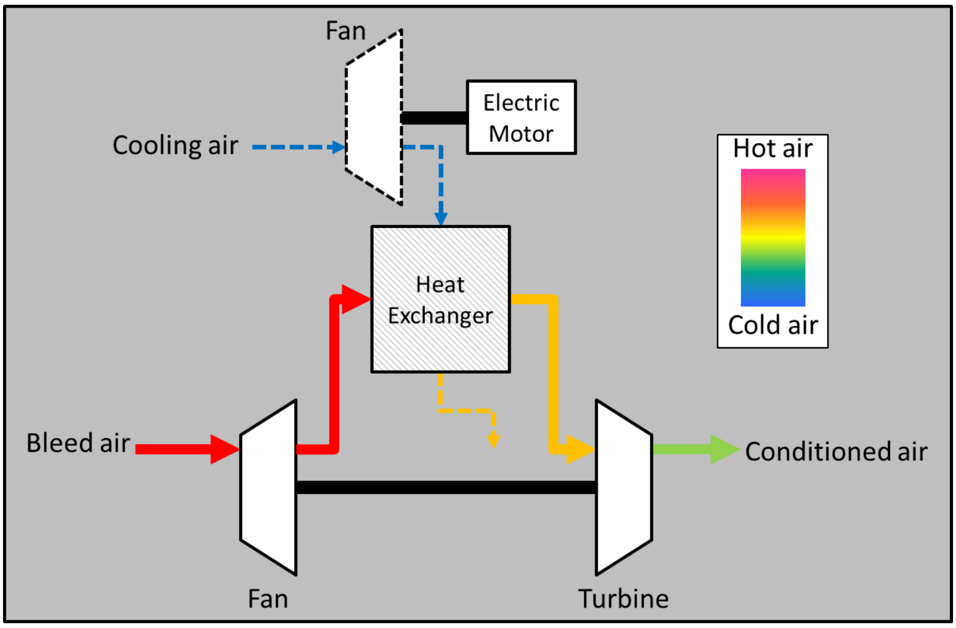


Figure 12: Air Cycle Machine - Bootstrap

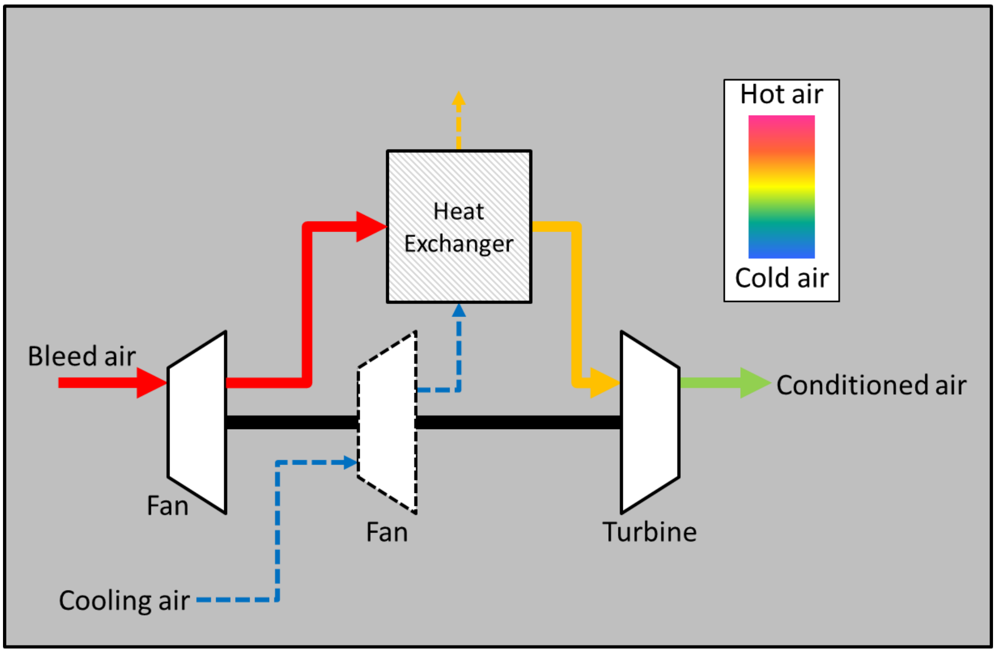


Figure 13: Air Cycle Machine - 3-Wheel

From the prevous analysis in the configuration of the Air Cycle Mahcine, the following equations have been taken. Those equations derive the main parameters mentioned in the subchapter 2.1, the pressure, temperature and mass flow.

Fan/Compressor outlet temperature

$$T_{Ccompressor} = \frac{T_{ATM}}{\eta_{compressor}} * \left[\Pi_{Compressor}{}^{\left(\gamma-1/\gamma\right)} - 1\right] + T_{ATM}$$

Turbine out temperature

$$T_{out} = T_{in} - \frac{PW_{shaft}}{\dot{m}_{bleed} \cdot C_p}$$

2.4. The Atmosphere

The earth atmosphere is an important field of consideration for ECS analysis since is the main aspect that affects its performance during a mission profile. Common civil aviation performs its activities in the troposphere which contains approximately the 80% of the complete atmospheric mass. The variation of the atmospheric parameters, such as temperature, pressure, density and speed of sound; are referenced by the International Standard Atmosphere model. The model gives the following reference data for sea level conditions.

Table 2: ISA sea level conditions

Typical Sea Level Conditions	
Temperature base	15 °C
Pressure	101353 Pa
Density	1.225 kg/m^3

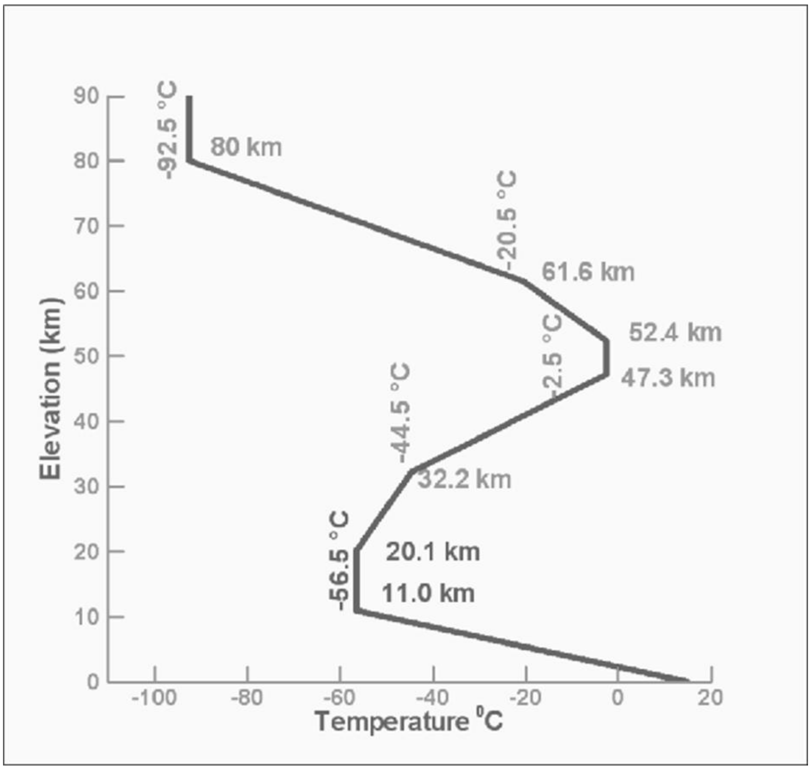


Figure 14: Temperature values for different altitudes at the atmosphere

For calculations of the atmospheric conditions, the following equations are used in ranges between 0 and 11000 meters above the sea level.

Temperature

$$T(h) = \left[T_{AMSL} - \left(\frac{T_{AMSL} - 216.66}{11000}\right) \cdot h\right] + \Delta T_{ISA}$$

Static pressure

$$\boldsymbol{P}(\boldsymbol{T}) = \boldsymbol{P}_{\boldsymbol{AMSL}} \cdot \left(\frac{\boldsymbol{T}}{\boldsymbol{T}_{\boldsymbol{AMSL}}}\right)^{\mathbf{5.256}}$$

Density

$$\rho(T,P) = \frac{P \cdot M_{air}}{T \cdot R}$$

Speed of sound

$$c(T) = 331.4 + 0.6 \cdot (T - 273.15)$$

2.5. Pressurisation

The main purpose of the pressurization aims to provide acceptable levels of oxygen for the passengers and crew. Basically, since the pressure levels at normal operation conditions are too low, with values around 25 kPa; the oxygen concentration is too low. Hence, the ECS needs to provide acceptable pressure levels for at least 75 kPa or the equivalent for an altitude of 2400 m above the main sea level. This value represents a pressure differential of around 50 kPa. Major values for a better cabin air quality, higher than 75 kPa, can be achieved on the cabin pressurization; but since the pressure differential would be higher, the security factor for the pressurized structure should be as well. Hence, for civil aviation the limits are conservative. The following figure shows the behaviour of the pressure at respective altitudes.

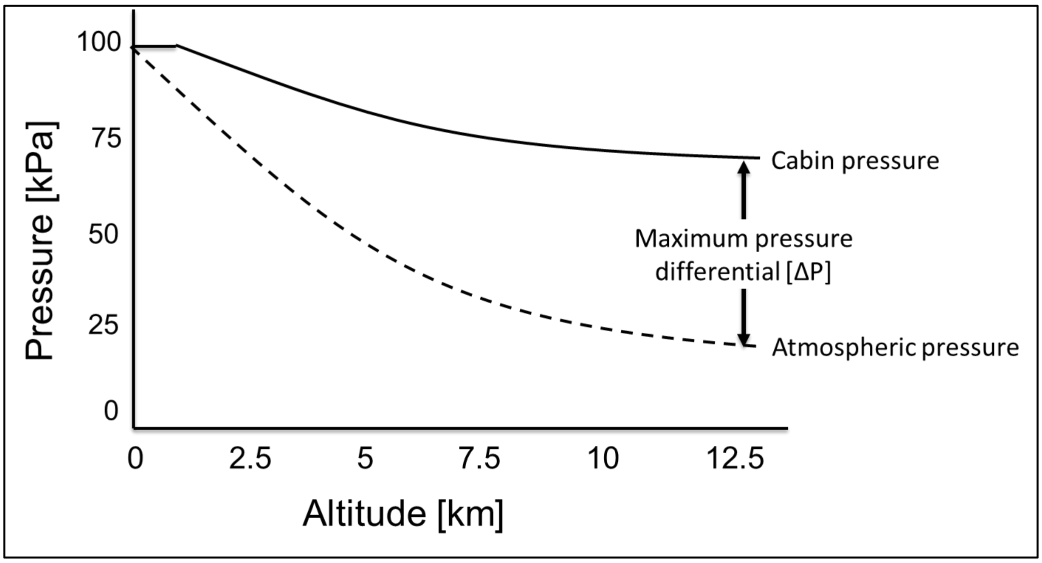
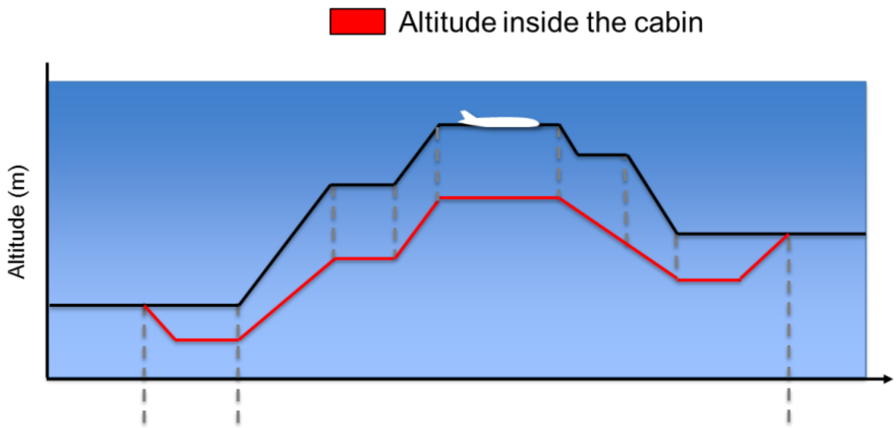


Figure 15: Pressure levels at different altitudes

Following the previous ideas, the pressurization is controlled automatically by a control unit. Aiming to achieve the previous requirements, this unit must achieve the following path in real mission profiles.



Cabin vertical speed	-	-400 ft/min		+500 ft/min	-
Cabin pressure differential ΔP	-	+0.1 PSI	≤ +8.06 PSI	+0.1 PSI	-

Figure 16: Cabin pressurization achieved by the control unit

For calculation purposes some equations have been considered form the field of fluid dynamics.

Pressure rate of change for entry flow

$$dP = \frac{\dot{m} \cdot R \cdot T}{V} dt$$

Pressure rate of change for the output valve

$$\mathrm{dP} = \frac{\sqrt{\frac{2 \cdot \gamma}{\gamma + 1}} A \cdot P \cdot \sqrt{R \cdot T}}{V} dt$$

2.6. Flow Distribution

For a manifold with one entry and two exits the temperature is calculates with the energy conservation principle:

$$T_3 = \frac{\dot{m}_1 \cdot T_1 + \dot{m}_2 \cdot T_2}{\dot{m}_1 + \dot{m}_2}$$

2.7. Cabin Thermodynamic Balance

The calculations of the thermal balance analyse the temperature behaviour through the time under certain conditions like, solar radiation, heat produced by passengers, atmosphere temperature and air ventilation for cabin temperature regulation. The following figures show the air distribution for the aircraft cabin; as seen, the air comes from the roof section towards the floor sections. This distribution path aims to reduce the possible biological effects, like virus or bacteria, that can be affect the passengers or crew members.

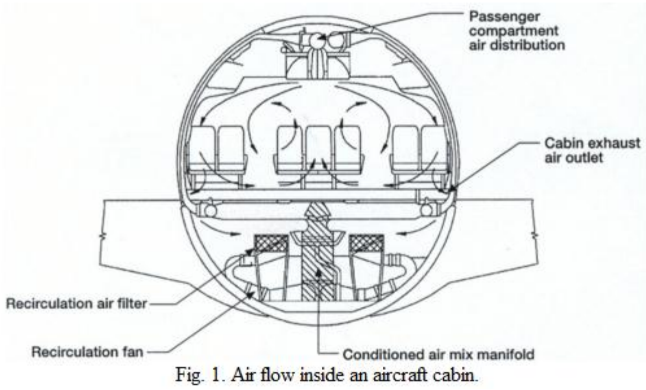


Figure 17: Airplane cabin air distribution

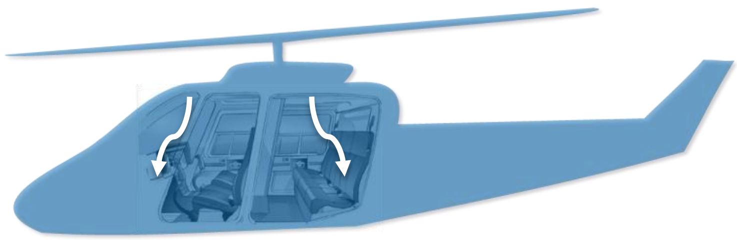


Figure 18: Helicopter air distribution

The results of the thermal balance give signals for the conditioning pack which allows it to control the air flow towards achieve a specific temperature given by the crew. The main calculations for the thermal balance come form the study of the first law of thermodynamics.

$$(E\dot{m}_{in} - E\dot{m}_{out}) + q_r + q_c + \sum q_G = \frac{\partial T}{\partial t}$$

Below is the appropriated equation to be used on the system, considering the current configuration.

$$(E\dot{m}_{in} - E\dot{m}_{out}) = \frac{V \cdot P}{R \cdot T_{out}} \cdot h_{air} \cdot (T_{in} - T_{out}) \cdot \dot{m}$$

Some aspects must be considered to perform thermal balance calculations, since are heat contributors.

Energy by solar radiation

$$q_{sr} = \sigma_{sr} \cdot A$$

Energy by convection

$$q_c = h \cdot A \cdot \Delta T$$

Energy generated in the system

$$\sum q_G = q_{passenger}$$

2.8. Heat Exchangers

The heat exchangers are an important component for the environmental control system. Its main function aims to reduce the high flow temperature which has been achieved through the flow compression.

Figure 19: [1]Heat Exchanger

Heat exchanger equation

The following equation has been considered to perform calculations on heat exchangers.

$$\dot{m}_{Cold} \cdot C_{P(Cold\ Air)} \cdot (T_{Cold2} - T_{Cold1}) = \dot{m}_{Hot} \cdot C_{P(Hot\ Air)} \cdot (T_{Hot2} - T_{Hot1})$$

2.9. Combustion Heating Principles

The Combustion Heater only provides heating, their disadvantages are presented with it high fuel consumption, which can only be affordable for small aircraft. This system works heating fresh air flow with a heat exchanger that receives heat from a combustion chamber; this process uses the convection principle of the thermodynamics.

[1] http://www.lytron.com/heat-exchangers/custom/heat-exchangers-plate-fin.aspx

Figure 20: [2]Combustion Heater

2.10. Airworthiness Requirements

For considerations of the ECS design; According to the Certification Specifications, for [8]Large Aeroplanes CS25 and [9]Large Rotorcraft CS29, an air flow of 0.3 m^3 are required, which are equivalent to a mass flow of 0.00645kg/s at an air density of 1.29kg/m^3 (such calculation is described with the following procedure. Even so, some [10]literature for engine design purposes establishes a mass flow of 0.0083kg/s, which is a higher value and with a better approach to be consider on this calculations.

$$m = \rho \cdot V$$

0.3m^3/min per passenger

0.005m^3/sec per passenger

$$\rho = 1.29 \text{ kg}/m^3$$

$$m = 0.00645\ kg$$

Minimum Fresh Air = 0.00645kg/s

[2] http://www.kellyaerospace.com/heaters.html

2.11. Models to Simulate the ECS

For simulation purposes of the ECS, the Flowmaster Group offers the software Flowmaster V7, which is capable of perform 1D Computational Fluid Dynamics (CFD). This tool allows the analysis and modelling of the fluid mechanics with diverse system configurations and distributions. The next figure shows a display of the software framework.

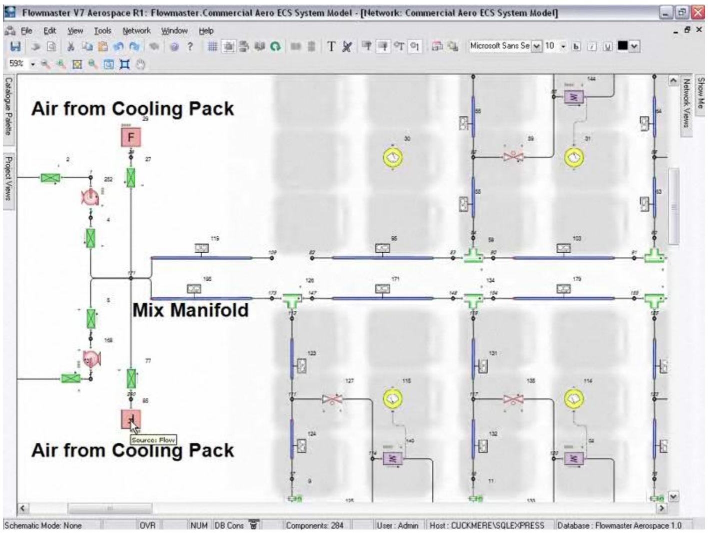


Figure 21: Flowmaster V7

2.12. New Technologies

For the new Boeing 787, a new all electric concept (AE-ECS) has been integrated by Boeing. This ECS doesn't use pneumatic power from the engine; instead of that it uses its electrical power to take air directly from the atmosphere. Compared to a bleed air system, this concept offers lower pressure and temperature for the Air Cycle Machine, therefore less energy loses as no pre-cooling is required. [11]Next table shows the air characteristics for concepts, the conventional and the more electrical.

Table 3: ECS concepts comparison

ECS	Temperature (°C)	Pressure (Pa)
Conventional	170	20.7
Electrical	100	11

Next table shows some [12]data for the All Electrical ECS in the Boeing 787.

Table 4: Data for the 787 ECS

Number of passengers	300
Cabin pressure at cruising	82kPa
Ram air compressors diameter	0.3m
Ram air compressors RPM	40000-50000
Ram air compressors pressure-ratio	5
Ram air compressors temperature increment	90°C
System weight	200kg
Estimated fuel saving	5000kg or 5%

On the other hand Airbus continues with the conventional ECS, but looks for an efficiency improvement with advanced engines, the RR Trent 1700 and the GE GEnx 1A.

2.13. The Fuel Penalty

For calculations of the fuel penalties, two methodologies have been analysed. The first methodology has been taken from the [13]Applied Thermodynamics Manual. The results for this methodology are presented on the annex B. The second methodology has been taken form the [11]lectures of the Dr C.P. Lawson and has been selected for this research, since the first one has presented difficulties to be applied for a rotary-wing aircraft and for the electric ECS.

Hence, from the Dr Lawson lectures, the following equation is used to obtain the increased weight of fuel used due to the system (ΔW_{FO}).

$$\Delta W_{FO} = \left(\Delta W_A + r\Delta D + \frac{r\Delta f_P}{c}\right) \cdot \left(e^{ctg/r} - 1\right)$$

Where,

$$\Delta W_A = System\ Weight$$

$$r\Delta D = \frac{Lift}{Drag} \cdot System\ Drag$$

$$\frac{r\Delta f_P}{c} = \frac{\frac{Lift}{Drag} \cdot (Fuel\ flow\ due\ power - off\ take)}{Specific\ Fuel\ Consumption}$$

$$t = time$$

$$g = gravity$$

Subsequently, the following equation is used to derive the fuel weight due to system weight.

$$(\Delta W_{FO})_{\Delta W_A} = \Delta W_A \cdot \left(e^{ctg/r} - 1\right)$$

Subsequently, the following equation is used to derive the fuel weight due to system power-off take.

$$(\Delta W_{FO})_{\Delta f_P} = \frac{r}{c}\Delta f_P \cdot \left(e^{ctg/r} - 1\right)$$

Subsequently, the following equation is used to derive the fuel weight due to system drag.

$$(\Delta W_{FO})_{\Delta W_A} = r\Delta D \cdot \left(e^{ctg}/r - 1\right)$$

2.14. Measurement

Two ideas are implemented to facilitate the calculation procedures. The first idea involves the application of the International Measurement System. Thus, the possibility by getting mistakes is minimized. The second idea looks for easy data reading and handling with the use of few decimals as possible, no more than thousandths as seen on the next figure.

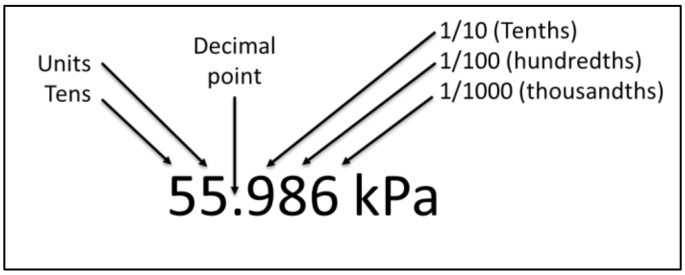


Figure 22: Decimals

Aiming to achieve this objective for easy understanding and mistake prevention, the appropriate mathematic conversions will be performed.

2.15. Cost Estimation

A [14]method proposed by Prof Dieter Scholz has been selected aiming to assess further impact in terms of direct operational cost for the ECS. This method called fundamental DOC_{SYS} is divided in three main contributions; System Depreciation, Fuel and Direct Maintenance Cost. For the case of this study, the System depreciation has been generalized to analyse the depreciation in 20 years. For Fuel Cost contribution, each one of the three different cases, presented in this research, is analysed. And for Direct Maintenance Cost a basic introduction of what can be expected is done.

$$DOC_{SYS} = Depr_{SYS} + Fuel_{SYS} + DMC_{SYS}$$

Depreciation Cost

$$Depr_{SYS} = \frac{Price - Residual}{N}$$

Where,

$$Price = price\ of\ the\ system$$
$$Residual = price\ of\ the\ system\ after\ N\ years$$
$$N = number\ of\ years$$

Following this methodology, the following chart has been generated to show how the system depreciation cost over its original value, for a period of 20 years. This study has been done with three different residuals, 0.15, 0.3, 0.45 and 0.6.

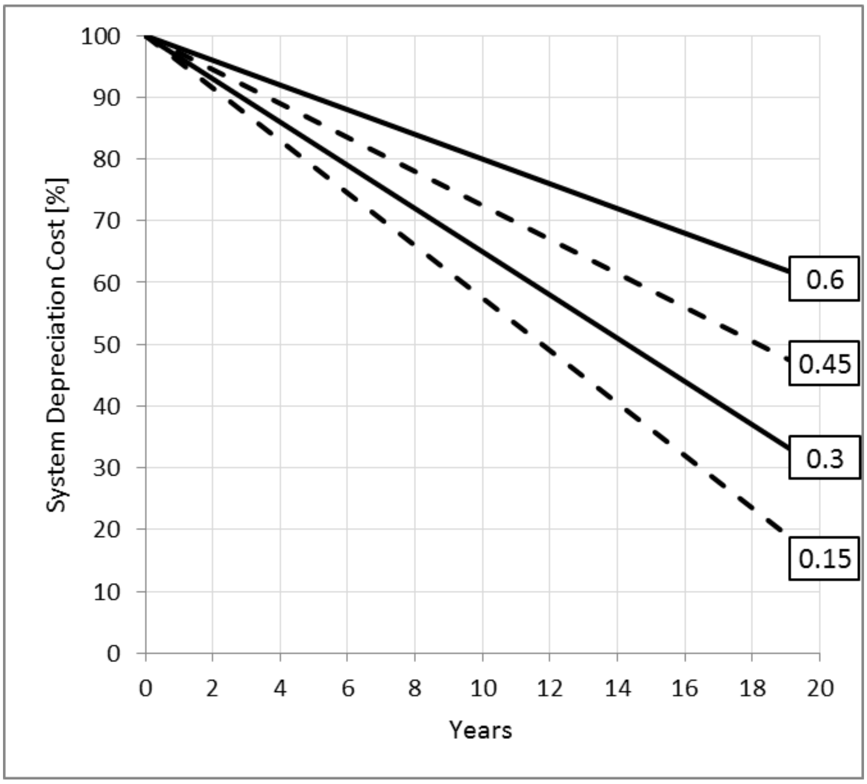


Figure 23: Depreciation over time

Fuel Cost

To assess the fuel cost this methodology is mainly based in the amount of fuel for the mission, the current fuel price and the number of this kind of flight missions per year. To assess the amount of fuel used in the mission, this methodology applies their respective methodology. For this research the methodology of Dr Lawson will be applied in conjunction with the overall study framework.

$$Fuel_X = m_{fuel,X} \cdot FuelPrice \cdot NFY$$

Where,

$$m_{fuel,X} = mass\ of\ fuel\ consumed\ due\ to\ cause\ Z\ during\ the\ whole\ flight$$

$$FuelPrice = current\ cost\ of\ fuel\ per\ kilogram$$

$$NFY = number\ of\ flights\ per\ year$$

Jet A-1 Price on 27 Nov 2011 [15]

Current price = 300.8 cents/gal

Jet A-1 Density = 0.804 kg/L

1gal=4.546 Litres

Then,

$$300.8\frac{\cancel{cents}}{\cancel{gal}} \cdot \left(\frac{1}{4.546}\frac{\cancel{gal}}{L}\right) \cdot \left(0.01\frac{USD}{\cancel{cent}}\right) = 0.66\ USD/L$$

$$0.66\frac{USD}{\cancel{L}} \cdot \left(\frac{1}{0.804}\frac{\cancel{L}}{kg}\right) = 0.822\ USD/kg$$

Direct Maintenance Cost

The calculation of direct maintenance cost requires exhaustive analysis. Therefore, the main methodology procedure is mentioned for future work. Hence the following equation describes this estimation.

$$DMC_{SYS} = \left(MMH_{on} - MMH_{off}\right) \cdot LR + MC$$

Where,

$$MMH_{on} = Maintenance\ Man\ Hours\ On\ Aircraft$$
$$MMH_{off} = Maintenance\ Man\ Hours\ Off\ Aircraft$$
$$LR = Labour\ Rate$$
$$MC = Material\ Cost$$

Aiming to support future research in the Direct Maintenance Cost, the following considerations should be taken. Those considerations have been established due to the new electric ECS components.

Table 5: Considerations for future direct maintenance cost estimations

Extra electric ECS Component	Note
Compressor for the ram air	• Degradation of the compressor materials which can generates reduction in its compression capability.
Electric motor	• Degradation of internal mechanism due to kinetic forces resulting in its torque capacity to move the compressor.
Wiring to run the electric motor	• Degradation of wiring due to external factors such as corrosion produced by hydraulic/oil/fuel fluids that could generate a short circuit.

On the other hand, since the new components of the electric ECS are not innovative, only its configuration; then is not expected a big cost increment for this maintenance estimation cost.

2.16. Airbus A321-200

The first of two models, which has been selected in the fixed-wing aircraft analysis, is the Airbus A321-200. This airplane, the largest version of the family A320, offers one of the best seat-mile cots against its competitors; putting this airplane on a big demand for the air transport market. This aspect makes the A321-200 a good model for this study.

The A321-200 has a narrow body configuration, which can accommodate up to 220 passengers on a single class configuration. Among its characteristics, the airplane has an overall length of 44.5 m; a range of operation of up to 5500 km and a maximum take-off mass of 95.5 tonnes. Those characteristics make the airplane a mid-range purpose. The following figure shows the A321-200.

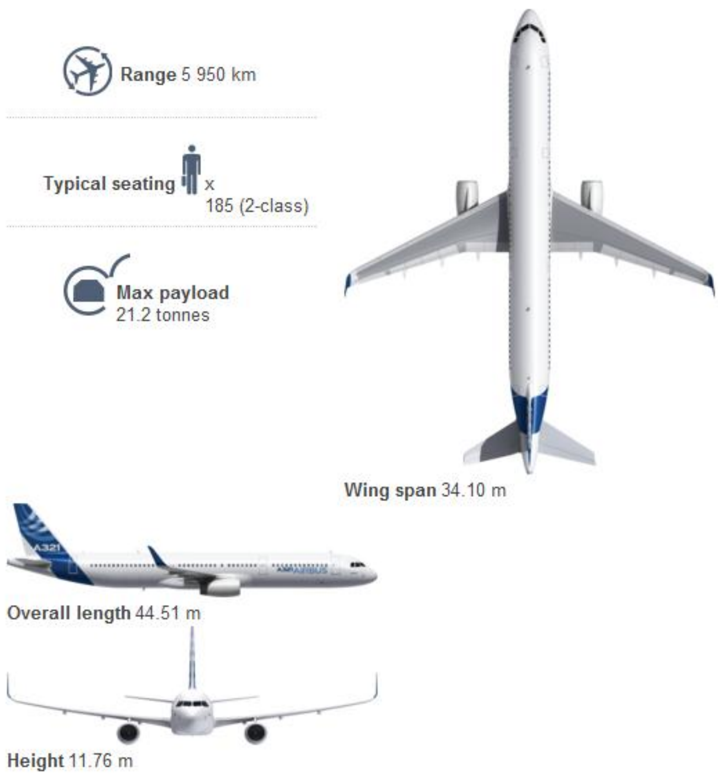


Figure 24: Airbus A321-200

This twin-engine airplane, which requires 148 kN per engine, can be powered with two engine options; the CFM56 or the International Aero Engines V2500. Been the first engine the most common. Its ECS is composed by an Air Cycle Machine which can be seen on the following figure.

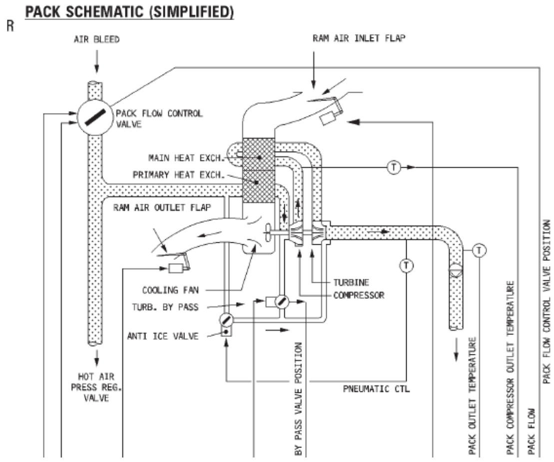


Figure 25: Airbus A321 Air Cycle Machine

The air distribution in the A321-200 follows a standard path, which is divided on three zones, the cockpit, forward and backward cabin sections. The air distribution can be seen on the following image.

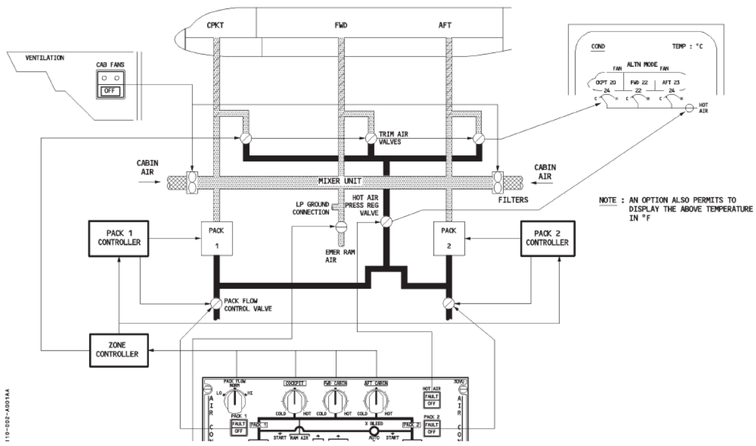


Figure 26: Airbus 321 ECS scheme

2.17. ATR 72-500

The second selected airplane to be case of study for this research is the [16]ATR 72-500. This airplane is a small regional civil fixed-wing aircraft, which can carry up to 74 passengers plus 2 crew members. This model is the latest development of the ATR 72 family. Among its characteristics, this airplane has a maximum range of 1800 km and is powered by two turbo-prop engines, the PW127F. The following figure shows the ATR 72-500.

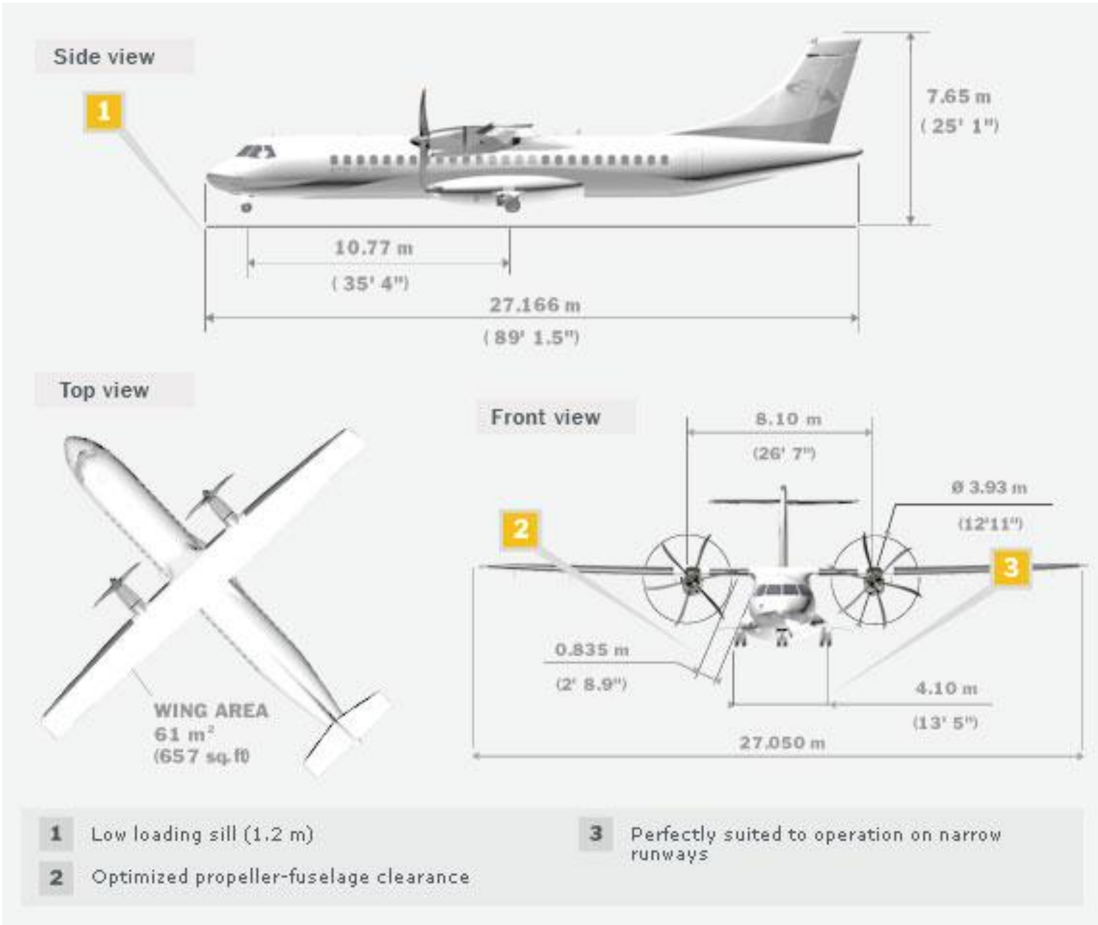


Figure 27: ATR 72-500

The cabin of the ATR 72-500 provides a pressurized environment. Since the main source of thrust comes from two turbo-prop engines the maximum altitude that the airplane can climb for cruise purposes is 7600m. The following figure shows the passengers cabin.

Figure 28: Cabin of the ATR 72-500

2.18. Bell 206

For rotary-wing analysis, the Bell 206 JetRanger has been selected as model of study. This helicopter is mainly operated for corporate transportation, gas and oils industries, law enforcement and fire fighting.

Figure 29: Bell 206

2.19. The Engine Performance Simulation Tool

Performance simulation tools are used for this research to carry out the calculations of Specific Fuel Consumption due to power off-take. Hence, Turbomatch of Cranfield University and Gasturb 11 Entry Level Version have been selected. Both tools were used to complement each other. This simulation is made in design point conditions for the cruise level.

[17]Turbomatch is a computational model based on a FORTRAN structure which can perform calculations of performance for gas turbine engines, basically through some input parameters which are the engine characteristics; those input parameters are written in a text format. The results on Turbomatch are generated in a format of text format which can be loaded in an excel table. The interface of Turbomatch is shown in the following figure.

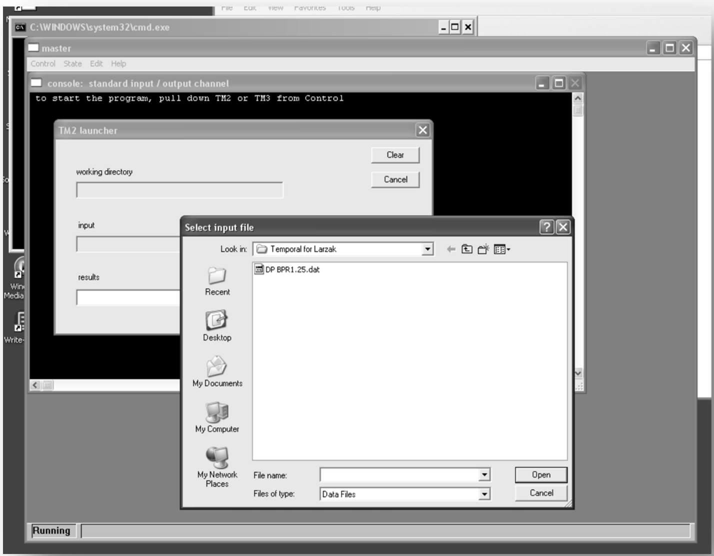


Figure 30: Turbomatch

[18]The GasTurb 11 Entry Level Version is a fully working program which can perform simulations for turbofan, turbojet, turboshaft and turboprop configurations. However, due to this is an entry level version it is limited to the Basic Scope except for the turbojet which allows unrestricted use of all programed options in the tool. The interface of Gasturb 11 Entry Level Version is shown in the following figure.

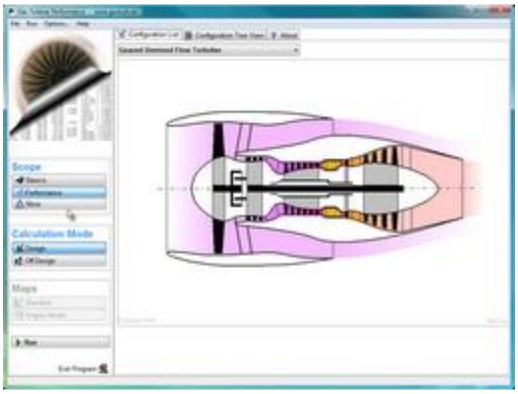


Figure 31: GasTurb 11 Entry Level Version

2.20. Engine Data for the Engine Performance Tool

To carry out the SFC increase ratio, the following inputs are taken for each engine. Those values are simulated in the cruise level conditions of each case of study.

Table 6: Engine inputs for the engine performance simulation tool

Parameters	Airbus 321-200 [CFM56-5b2]	ATR 72-500 [PW127F]	Bell 206 [Allison 250 C20J]
Mass Flow [kg/s]	433.6	7	1.23
By Pass Ratio – Turbofan engines [BPR]	5.5	-	-
Overall Pressure Ratio [π_O]	35.5	14-17	6.2
Fan Pressure Ratio – Turbofan engines [π_F]	1.7	-	-
Compressor Pressure Ratio [π_C]	1.8	-	-
HPC [π_{HPC}]	11.6	-	-
TET [K]	1700	1550	1550

CHAPTER 3 | THE METHODOLOGY OF ANALYSING THE ENVIRONMENTAL CONTROL SYSTEM

3.1. Research Framework Process

The analysis of the energy management on a system is complex. Therefore, a research framework has been designed aiming to provide a schematized and reliable process to achieve the main objective, simulate both ECS models; the conventional and the electric ones. This framework has been divided in 5 main steps, beginning with the aircraft selection and ending up with the system penalties comparison. The following figure shows the proposed framework.

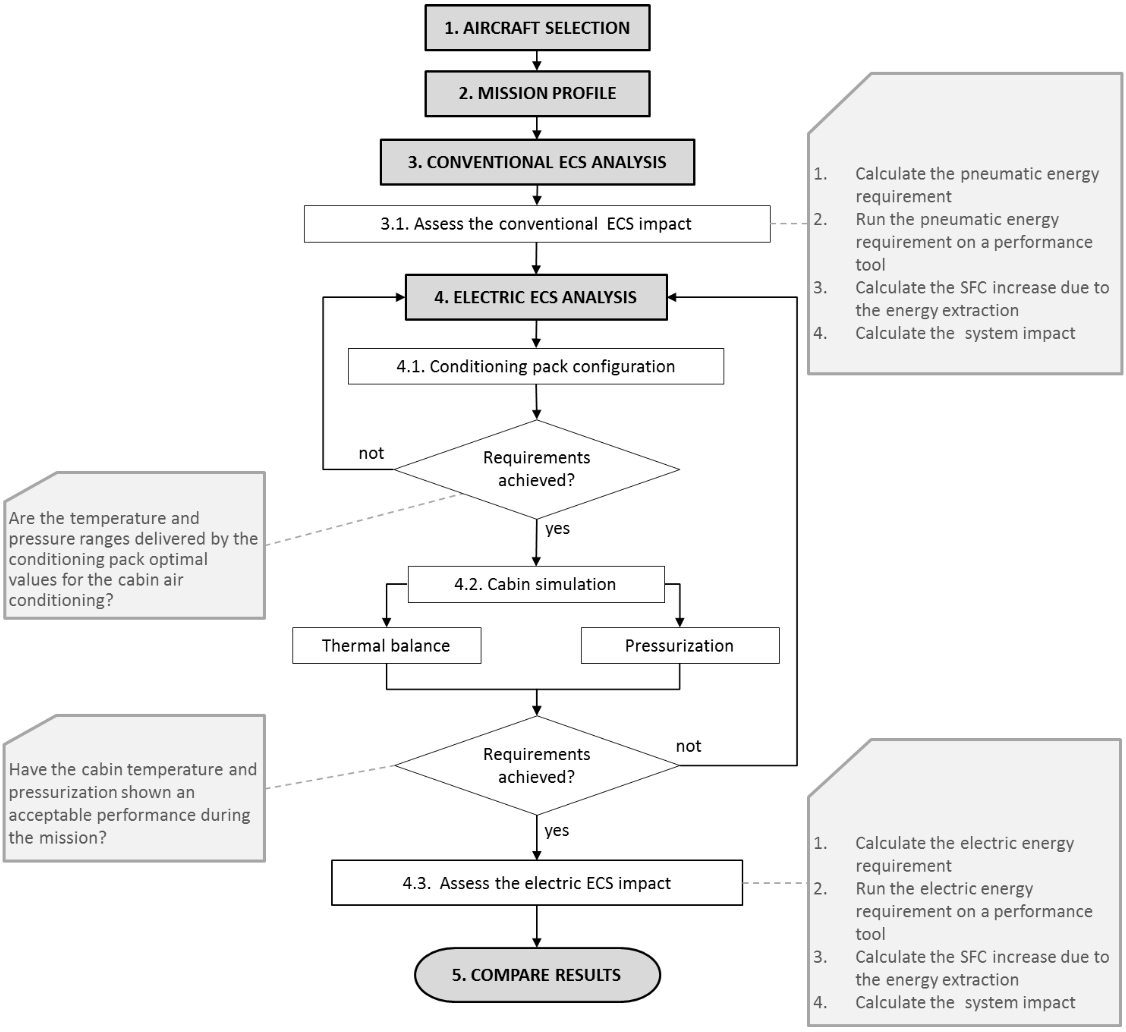


Figure 32: Detailed flowchart for the analysis process

Aircraft Selection

Describing the simulation process with the algorithm of the previous figure, the first step involves establishing the requirements, which are parameters that are fixed for a specific aircraft model and cannot be changed like the geometry or the number of passengers.

Mission Profile

The next stage sets up the mission profile parameters, which are established by the ambient conditions regardless the flight altitude, and temperature selected by the crew. A powerful flight path has been created inside ELENA. Such flight path can follow a mission with three stages; climb, cruise and descent. Therefore some basic inputs need to be loaded, such like departure altitude, rate of climb, cruise altitude, cruise Mach number, cruise range, rate of descent and destination airport. The following figure has been generated to show this scheme.

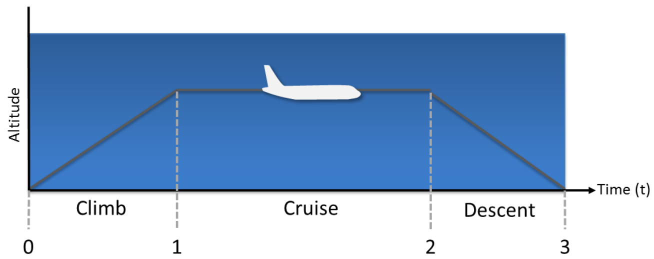


Figure 33: Mission profile for ELENA

Conventional ECS analysis

The third stage aims basically to establish the energy penalties produced by a conventional ECS. At this point the required pneumatic energy is calculated for this particular aircraft. For the next task it is necessary to use a performance simulation tool like Turbomatch or Gasturb; hence, the engine performance is simulated to assess the increment on the Specific Fuel Consumption due to this pneumatic energy. The inputs taken in account for this simulation are listed in the table 5 and are based on the cruise altitude. Subsequently this increment percentage in SFC is used in ELENA. Hence, the fuel penalty is assessed in conjunction with other parameters; such as the system drag and system mass contribution. If the results are acceptable with the real ones, the simulation process can be finished and continued to the next step.

Electric ECS analysis

The next step aims to set up electric ECS configuration. Hence, following the main purpose of the flow chart, this configuration can be changed towards achieving a system that is capable to meet the air conditioning requirements for the selected aircraft. Those requirements are mainly the temperature control and the pressurization if the aircraft is a fixed-wing type.

Hence, aiming to develop a reliable analysis for the electric conditioning pack design, this stage has been divided into three main steps. Firstly, a small parametric study is done to establish the configuration for an electric ECS conditioning pack which is capable to meet the flight mission requirements.

Secondly, the cabin temperature and pressurization are simulated to analyse the response of the configured conditioning pack for a mission profile. The mission profile includes the three main flight phases, climbing, cruise and a descent.

And finally, the fuel penalty is assessed in conjunction with other parameters; such as the system drag and system mass contribution. If the results are acceptable the simulation process can be finished and continued to the final step. This step is done with the same methodology for the conventional ECS, with the difference that the power off take will be electrical and not pneumatic.

Results comparison

The main goal in the final step is to compare the results for both, the conventional and electric ECS’s. Hence, is possible to analyse on a first view the achievements, advantages and disadvantages for an electric ECS.

3.2. The Software for Analysis

The ECS Model was developed with Simulink® which allows an easy integration with the other systems. An interface was built to provide a structured method to place inputs and display outputs, and to be properly configurable with Simulink® as well. To define the level of accuracy some parameters were considered in the next table. A mid accuracy method was selected for the simulation model.

Table 7: Level of model accuracy

MID	HIGH
REQUIREMENTS: • Airplane basic Internal Geometry • Type of condition pack PROS: Can be used easily with any other aircraft model and for energy consumption estimations. CONS: Is not suitable for a detailed analysis of a specific aircraft, especially for real design process.	REQUIREMENTS: • Airplane detailed Internal Geometry • ECS distribution (Pipe lines, geometry, materials) • Real ECS Automatic Operation PROS: Is more accurate for a single analysis and real design processes CONS: Require a specific configuration for each specific aircraft model. Requires confidential design data.

3.3. ELENA v1 – Environmental Control System Analysis Tool

Framework scheme

A general framework for ELENA was designed, taking the concepts and equations to establish the simulation code. For rotary-wing analysis, an initial model has been used but only considering the combustion heating calculations. This initial model was created on the first stage of the research. The next figures have been generated to show the framework for both aircraft types.

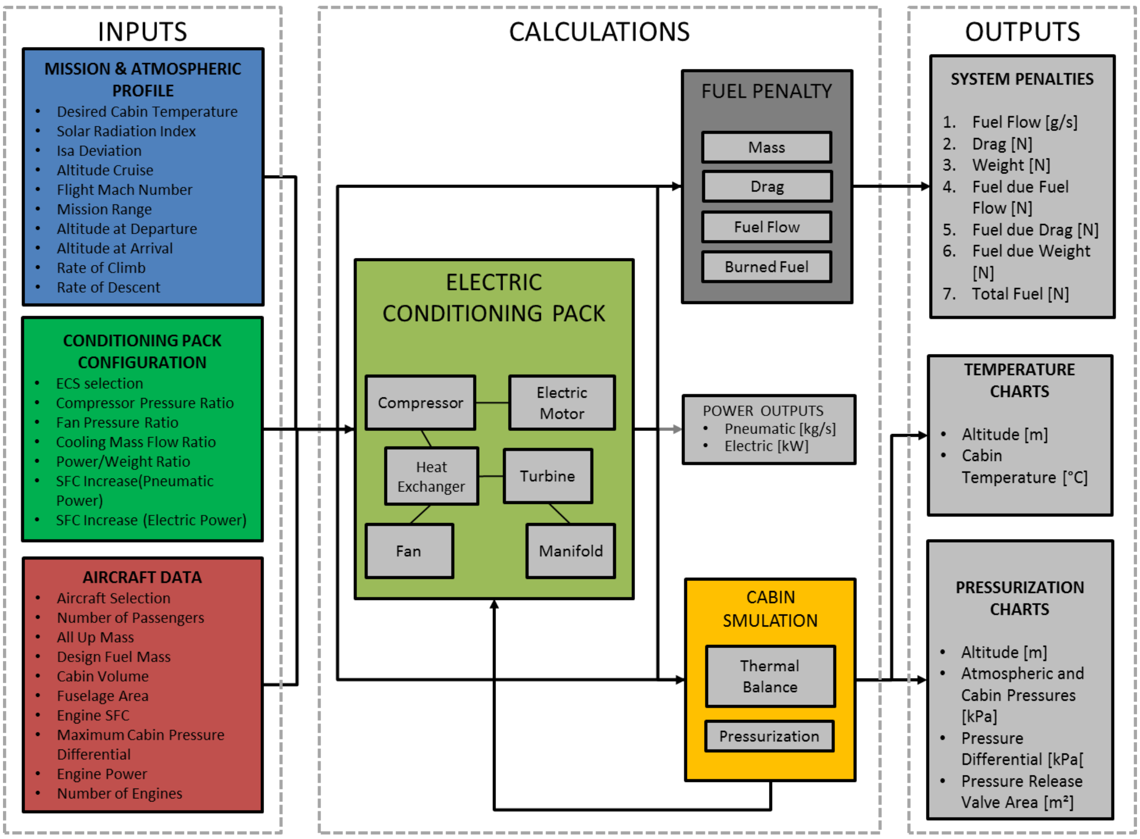


Figure 34: Simulation framework for ELENA v1

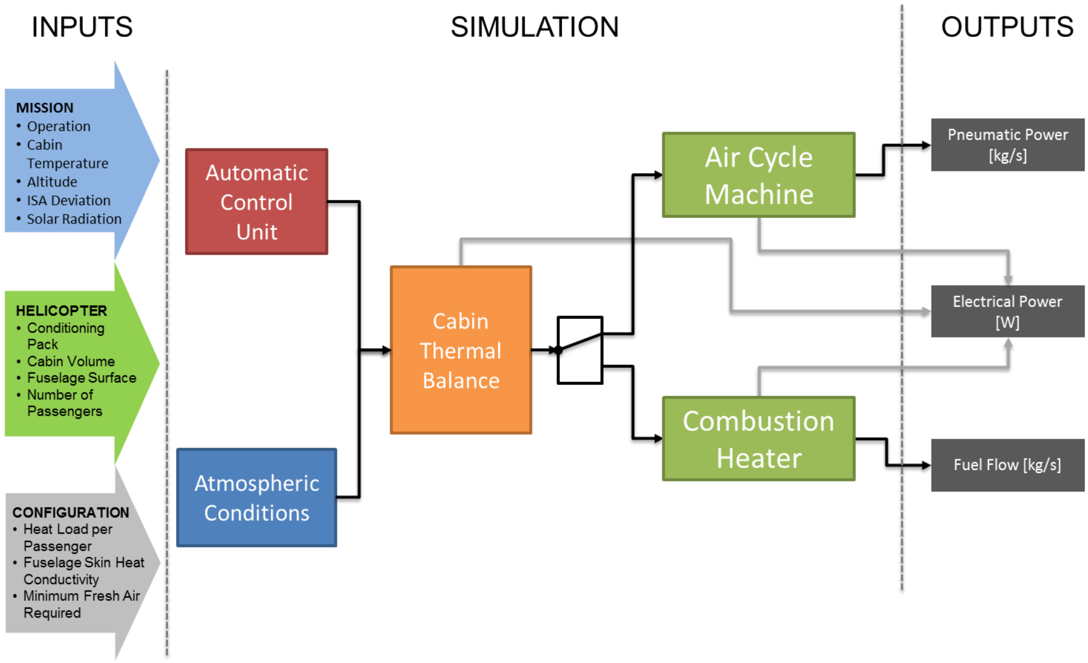


Figure 35: Simulation framework for the rotary-wing aircraft

Simulink scheme

To understand the model ELENA is necessary to recognize its interface on Simulink®. As seen on the sollowing figure, its scheme is similar to that one proposed on the previous figures. This capability makes Simulink® a powerful tool for calculations and simulation purposes.The main interface contains a region for Inputs, located at the left; and another for Outputs located at the right, the boxes or modules are the processing units and contain all the code which allows the simulation to be carried out. The interconnection lines send information between inputs, boxes and outputs. The gross lines are buses, which can carry a huge group of values; hence, the model becomes easier for handling on.

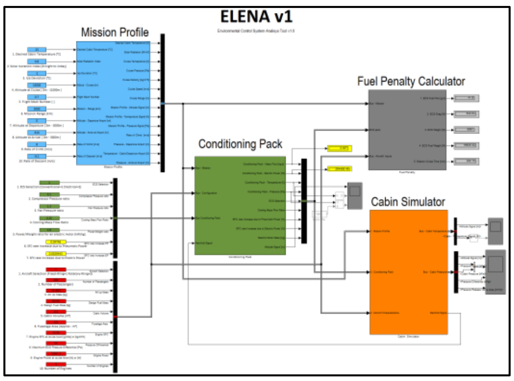


Figure 36: Final version of the Simulink model ELENA

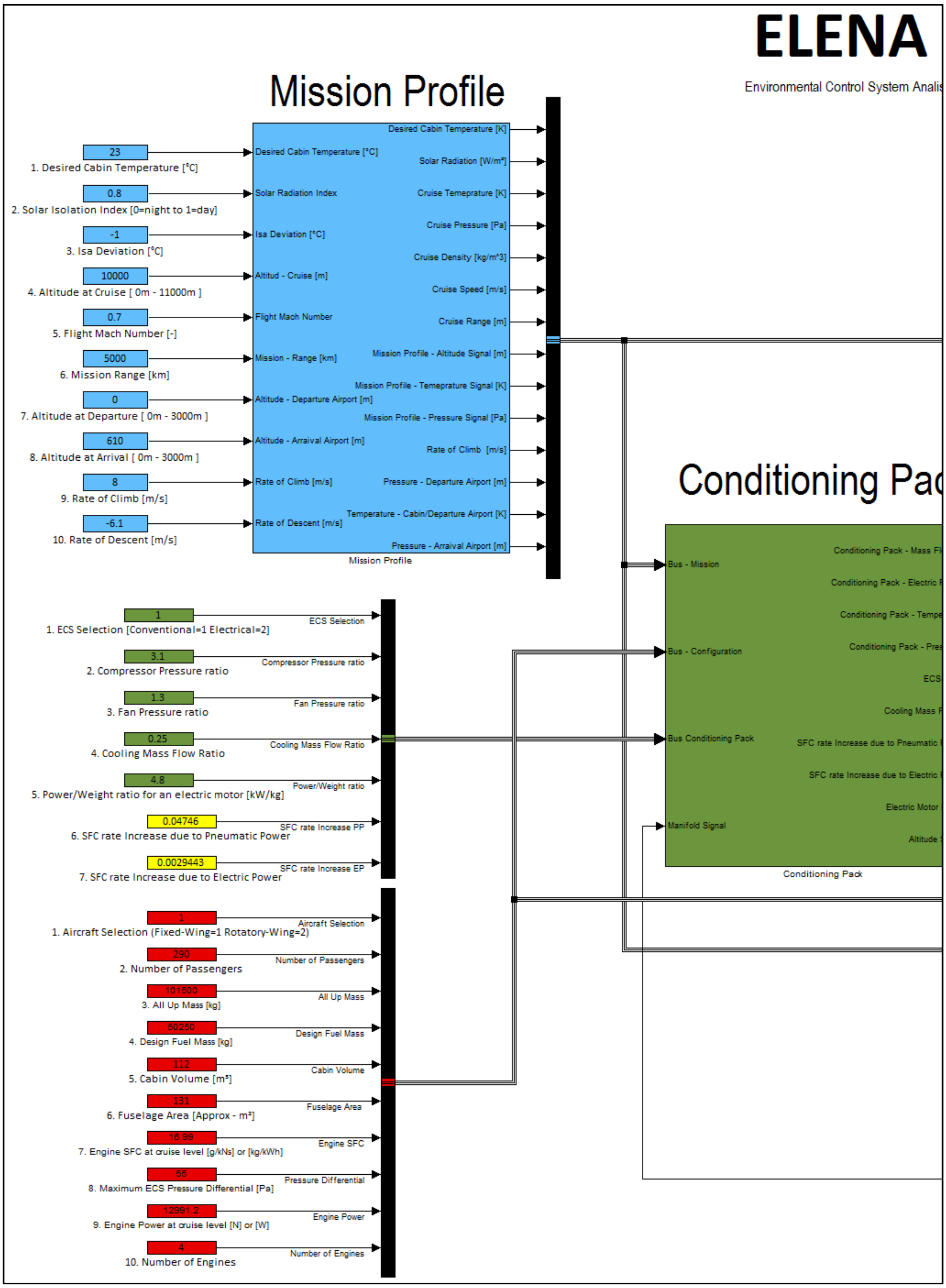


Figure 37: Final version of the Simulink model ELENA (Left view)

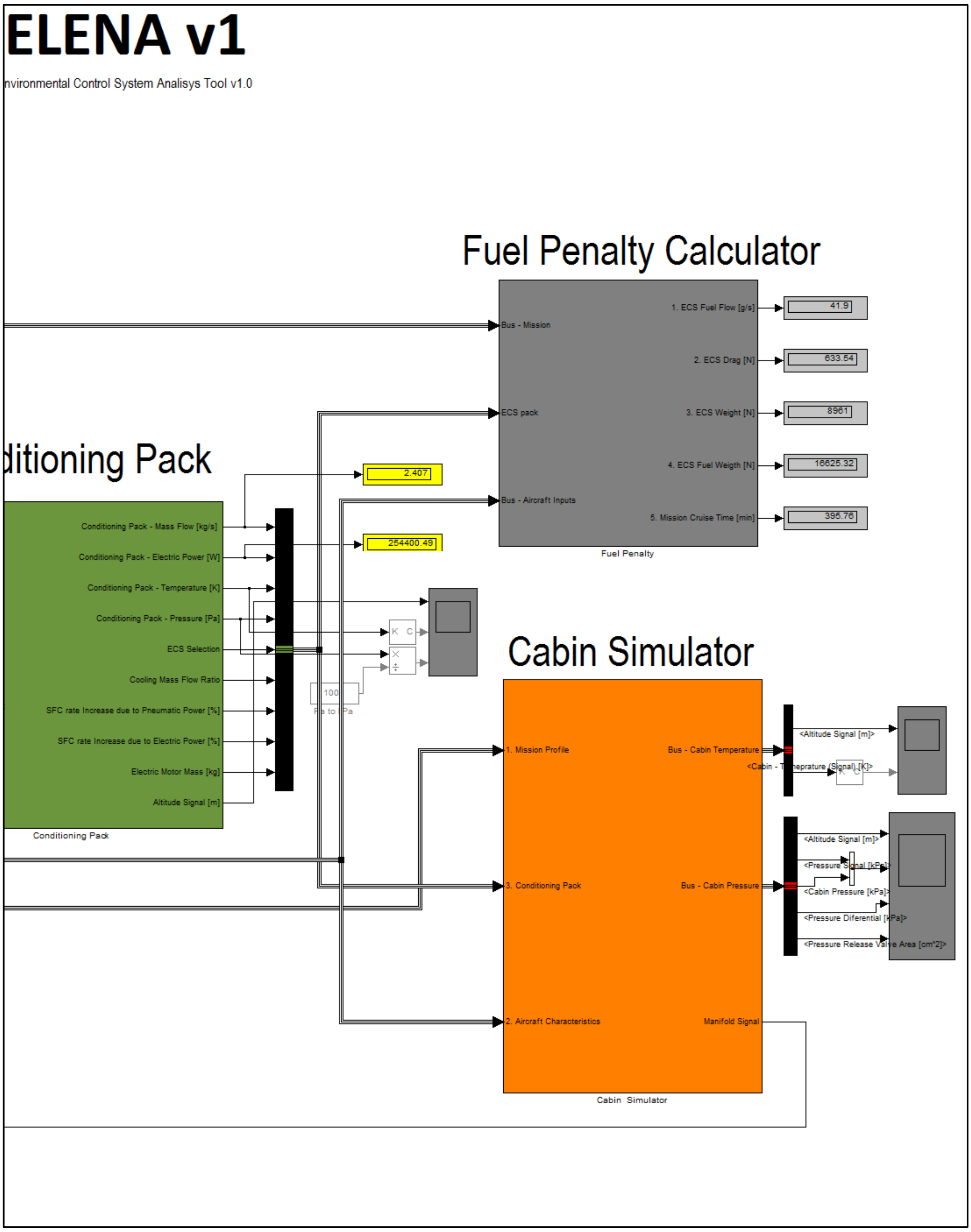


Figure 38: Final version of the Simulink model ELENA (Right view)

The following figure shows the Simulink® model of a previous version which was created on the first stages of this research. This model in difference to ELENA only was capable to simulate rotary-wing aircraft. Its main outputs required mass flow if the air cycle machine is selected or the fuel flow if the combustion heater is selected; and the electric power consumed by minor components in any of both systems. This model is other different and interesting approach with different inputs and outputs, and will be considered only for combustion heater calculations in the helicopter.

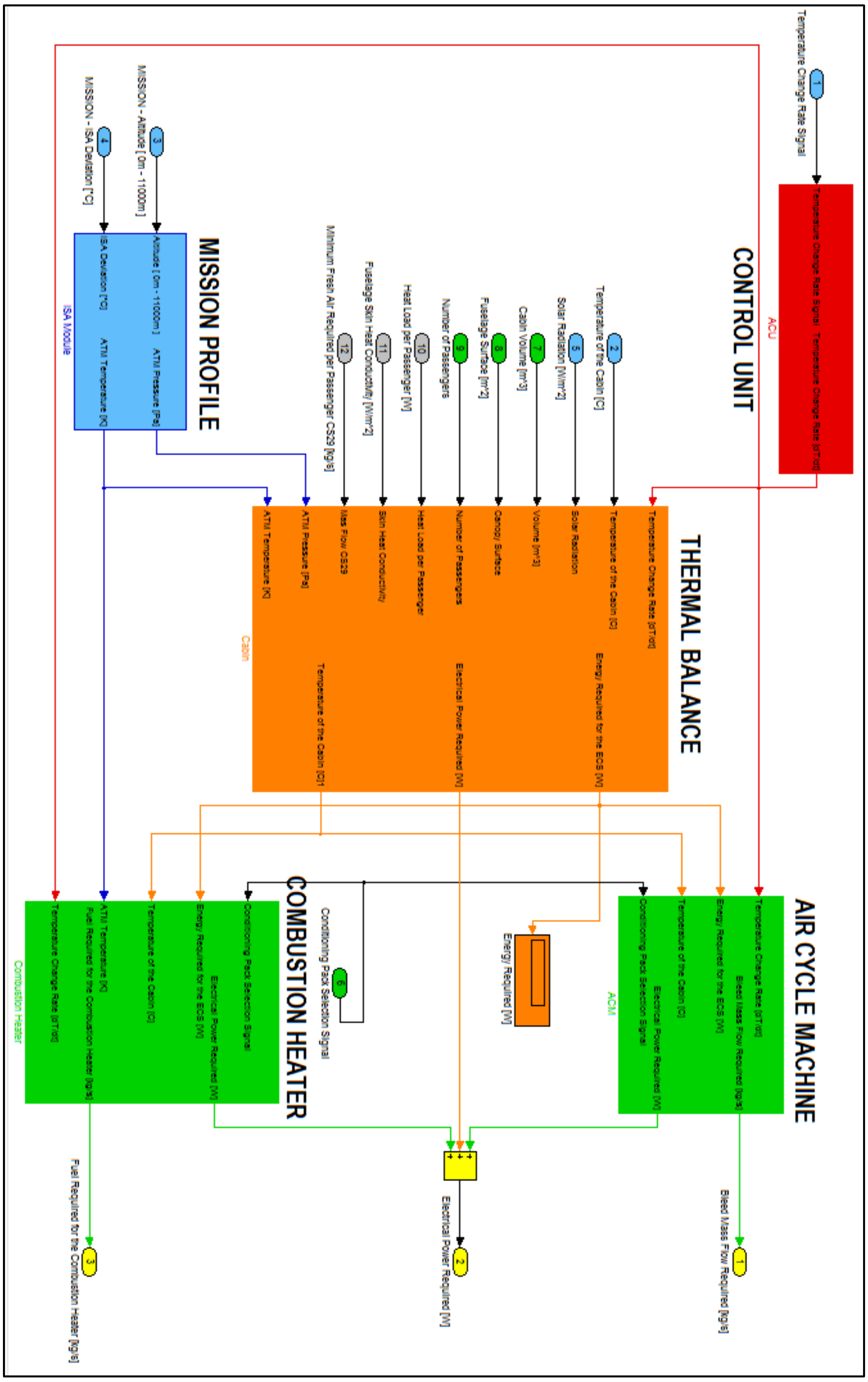


Figure 39: Simulink model for the rotary-wing aircraft

3.4. AIRCRAFT INPUTS

Describing the simulation process with the algorithm of the previous figure, the first step involves establishing the requirements, which are parameters that are fixed for a specific aircraft model and cannot be changed like the geometry or the number of passengers. As seen; all the inputs are the standard requirement for this analysis, to be carried out.

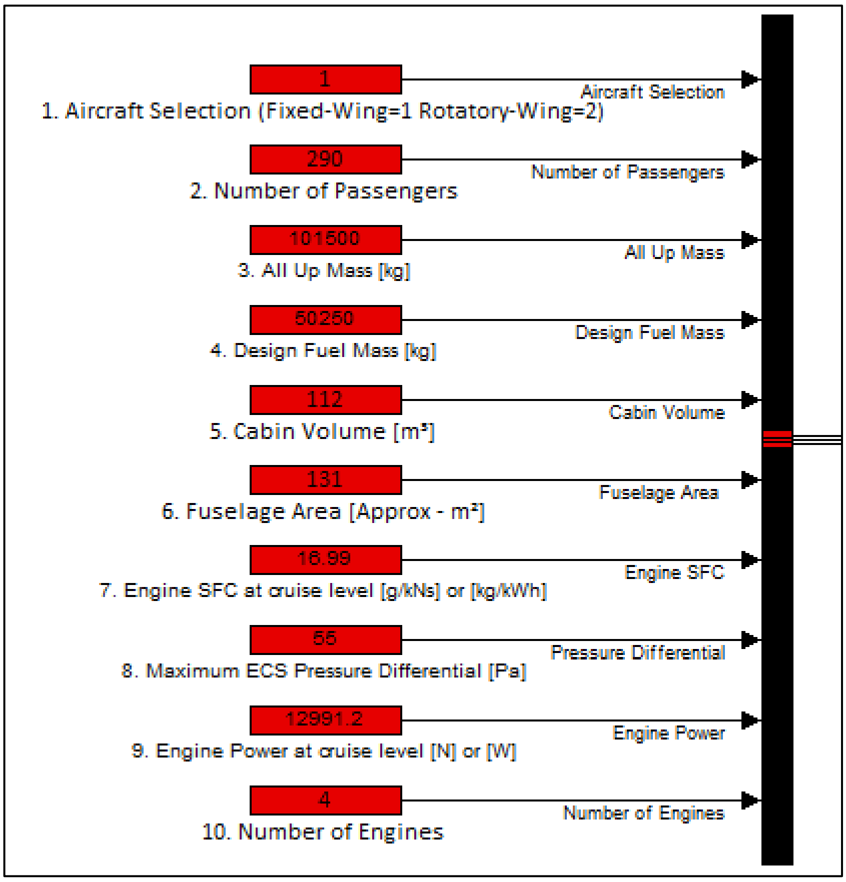


Figure 40: Aircraft Database Characteristics

The following table shows the data with its nomenclature, which has been selected on International Metric System.

Table 8: Aircraft inputs

Input	Units	Optimal range
1. Aircraft selection signal	-	1=(Fixed-Wing) 2=(Rotary-Wing)
2. Number of passengers [PN]	-	[0 to 800]
3. All up mass [AUM]	kg	[1000 to 500000]
4. Fuel weight [W_F]	kg	[50 to 80000]
5. Cabin Volume [V_{cab}]	m^3	[10 to 1000]
6. Fuselage Area [A_{fus}]	m^2	[2 to 2000]
7. Engine SFC [SFC]	g/kNs (Turbojet) kg/kWh (Turbo-prop/shaft)	[2 to 40] [0.2 to 0.4]
8. Maximum Pressurization Deferential [ΔP_{MAX}]	kPa	[about 55 kPa]
9. Engine net thrust or net shaft power at cruise [FN] or [PW]	N or W	[50000 to $2X10^6$]
10. Number of engines [EN]	-	

3.5. MISSION PROFILE CALCULATIONS

As mentioned previously; the next stage sets up the mission profile parameters which are established by the ambient conditions regardless the flight altitude, and temperature selected by the crew. A powerful flight path has been created inside ELENA. Such flight path can follow a mission with three stages; climb, cruise and descent. Therefore some basic inputs need to be loaded, such like departure altitude, rate of climb, cruise altitude, cruise Mach number, cruise range, rate of descent and destination airport. The following figure shows the inputs and the module for mission profiles calculations, both part of ELENA.

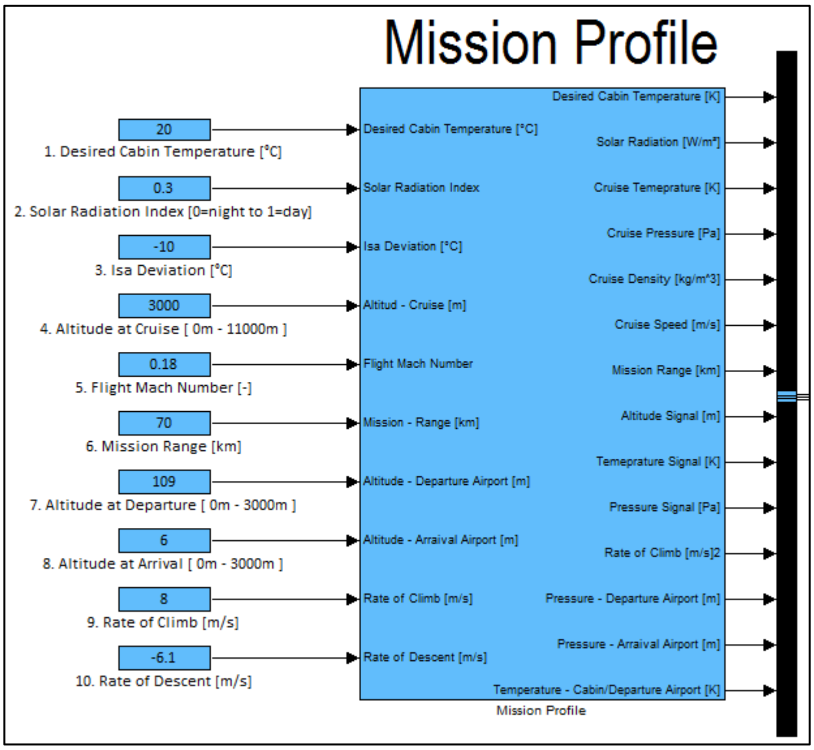


Figure 41: Mission Profile Module

Inside this module, various calculations are performed aiming to achieve the complete flight path with all its three phases, climb, cruise and descent. The following figure shows an approach of this module content.

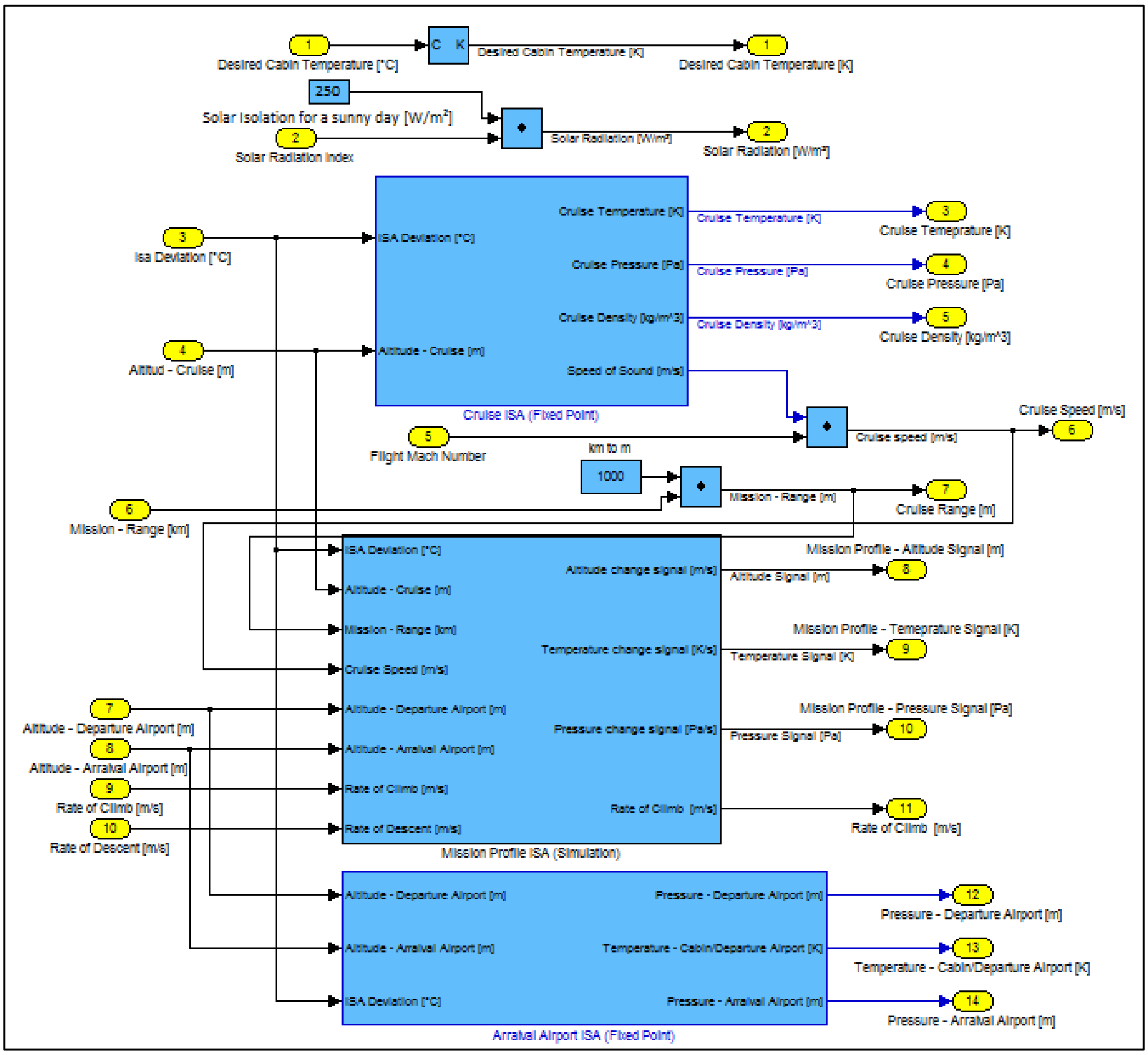


Figure 42: Content for the box of mission profile calculations

Mission Inputs

Once the previous scheme has been programed in for ELENA, a case study can be carried out using the next inputs.

Mission Inputs:

Table 9: Mission Inputs

Input	Units	Optimal Range
1. Departure airport/Cabin - Initial temperature (T_{0ab})	°C	[-5 to 30]
2. Solar Isolation Index (SRI)	-	[0 to 1]
3. Isa deviation (ΔT_{ISA})	°C	[-20 to 25]
4. Aircraft cruise altitude (h_{1-2})	m	[0 to 11000]
5. Flight Mach number (Ma)	-	[0 to 0.9]
6. Cruise range (d_{1-2})	km	[0 to 20000]
7. Departure airport altitude (h_0)	m	[0 to 3000]
8. Arrival airport altitude (h_3)	m	[0 to 3000]
9. Rate of Climb (vs_{0-1})	m/s	[1 to 8]
10. Rate of Descent (vs_{2-3})	m/s	[-1 to -6]

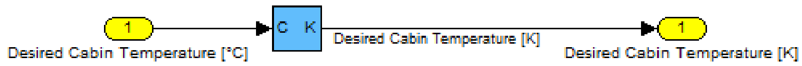
A Sun Heat Index has been integrated with values ranging from 0 to 1. A minor value, approximated to 0 means no sun heat radiation or a night condition. A major value near 1 means a sunny day condition with an average of 250 W/m^2.

Mission Outputs

Desired cabin temperature

Following standardization, the cabin temperature is managed as Kelvin nomenclature. Since the values are placed in Celsius degrees for easy model management, the following equation is used. This equation delivers the temperature with Kelvin nomenclature.

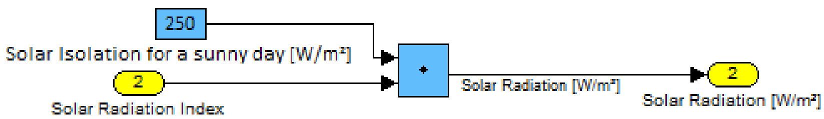
$$T_{(kelvin)} = T_{(celcius)} + 273.15$$



Solar radiation

For easy management of the model, an Index (SRI) value has been applied for the solar radiation conditions. This index value is considered on a range between 0 and 1. The average value that the solar radiation can achieve on the atmosphere, 250 W/m^2, is associated to 1. On the other hand the value of 0 represents nocturnal conditions; and a value of 0.5 would represent cloudy days.

$$r_{sr} = SRI \cdot (250)$$



Cruise Values

The following calculations were carried out to find the values of pressure, temperature, density and speed of sound for given altitude and ISA deviation. The following figure shows its programing inside ELENA.

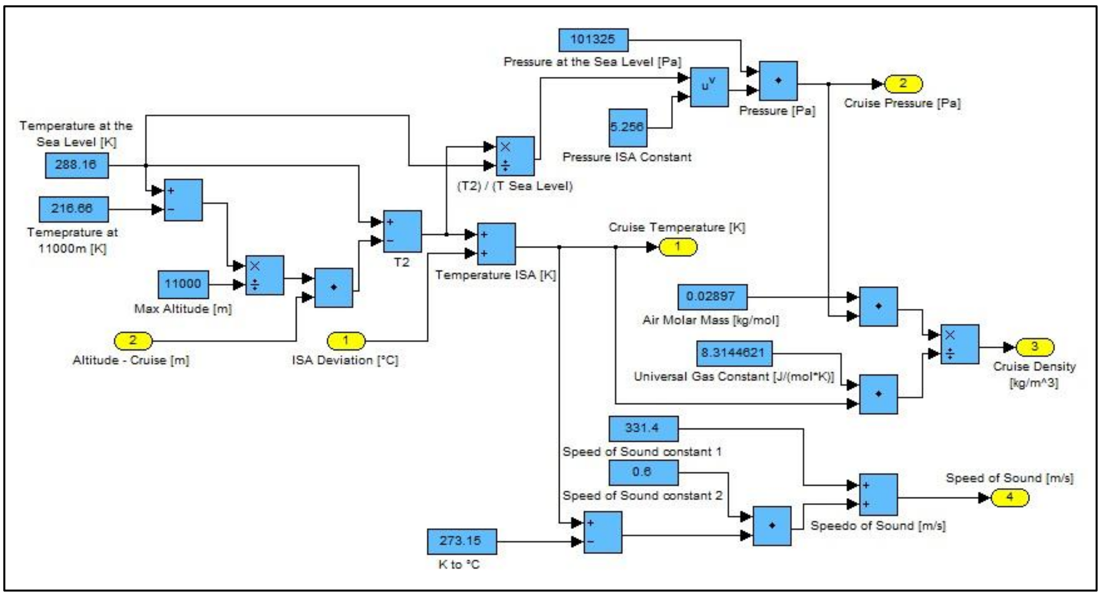


Figure 43: Mission cruise calculations in ELENA

The cruise temperature is given by the following calculations:

$$T_{(1-2)} = \left[T_{AMSL} - \left(\frac{T_{AMSL} - T_{h_{max}}}{h_{max}}\right) \cdot h_{(1-2)}\right] + \Delta T_{ISA}$$

Where,

$$T_{h_{max}} = 216.66\ K$$

$$h_{max} = 11000\ m$$

$$T_{AMSL} = 288.15$$

The cruise pressure is given by the following calculations:

$$P_{(1-2)} = P_{AMSL} \cdot \left(\frac{T_{(1-2)}}{T_{AMSL}}\right)^{5.256}$$

Where,

$$P_{AMSL} = 101325\ Pa$$

The cruise density is given by the following calculations:

$$\rho_{(1-2)} = \frac{P_{(1-2)} \cdot M_{air}}{T_{(1-2)} \cdot R}$$

Where,

$$M_{air} = 0.02897\ kg/mol$$

$$R = 8.314\ J/(K \cdot mol)$$

The cruise speed of sound is given by the following calculations:

$$c_{(1-2)} = 331.4 + 0.6 \cdot (T_{(1-2)} - 273.15)$$

The cruise range is given by the following calculation, which basically converts km to m:

$$d_{(1-2\ m)} = d_{(1-2\ km)} \cdot 1000$$

The aircraft speed is given by the following calculations:

$$v_{(1-2)} = c_{(1-2)} \cdot Ma$$

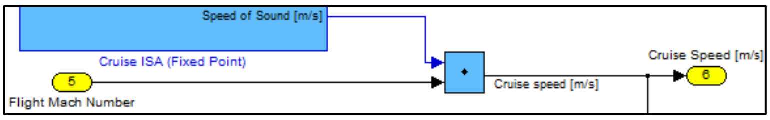
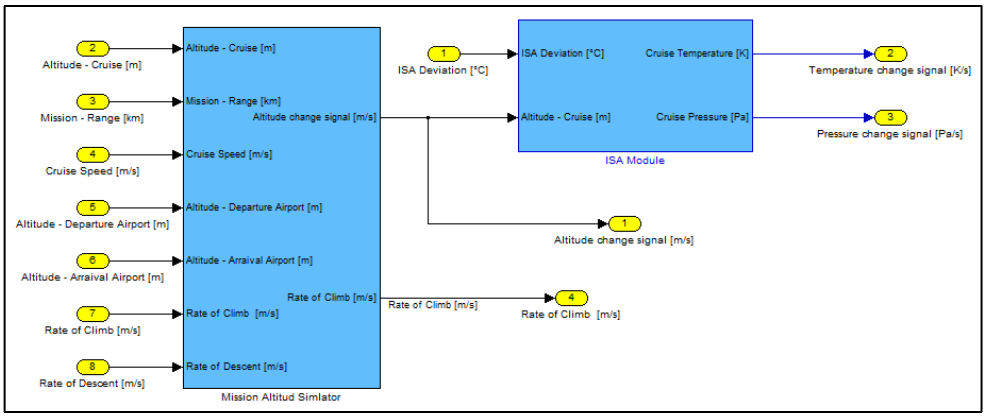


Figure 44: Aircraft speed calculation in ELENA

Mission profile signals

To generate flight path for a mission profile with three stages is necessary to create an algorithmic process similar to any one programed for a real ECS control unit. The following figure shows the boxes that calculate and generate this flight path in ELENA; in the left side is seen the box for the algorithmic code that generates the altitude signals and in the right side is the box that calculates temperature and pressure for all the generated altitude signals.



Following the main concept for the mission profile; since the equations to calculate atmospheric temperature and pressure are in function of altitude, an algorithm was created to generate the altitude for the mission profile. This profile is composed by three stages, climb cruise and descent. Once this altitude signal is provided by the algorithm, it is possible to calculate the temperature and pressure for the complete mission profile.

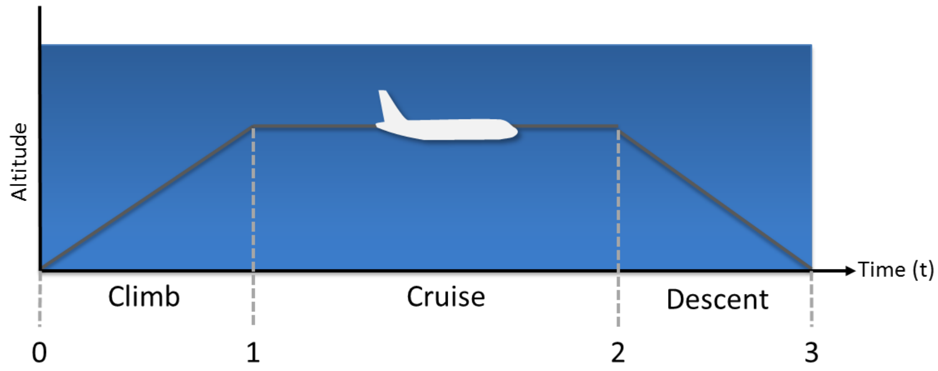


Figure 45: Flight path to be followed by the algorithm

The algorithm is described with the following equation and commands.

$$h_{ATM} = h_0 + \frac{\partial vs}{t}$$

Where,

$$IF \quad \boldsymbol{t} < t_1 \quad THEN \quad \frac{\partial vs}{t} = vs_{rate\ of\ climb\ (0-1)}$$

$$IF \quad t_1 \leq \boldsymbol{t} < (t_1 + t_2) \quad THEN \quad \frac{\partial vs}{t} = 0$$

$$IF \quad (t_1 + t_2) \leq \boldsymbol{t} < (t_1 + t_2 + t_3) \quad THEN \quad \frac{\partial vs}{t} = vs_{rate\ of\ descent\ (2-3)}$$

$$IF \quad (t_1 + t_2 + t_3) \leq \boldsymbol{t} \quad THEN \quad \frac{\partial vs}{t} = 0$$

Where,

$$\boldsymbol{t} = \partial t\ time\ signal\ generated\ in\ Simulink$$

$$t_1 = \frac{(h_{(1-2)} - h_{(0)})}{vs_{rate\ of\ climb\ (0-1)}}$$

$$t_2 = \frac{d_{range(1-2)}}{v_{cruise\ (1-2)}}$$

$$t_1 = \frac{(h_{(3)} - h_{(1-2)})}{vs_{rate\ of\ descent\ (2-3)}}$$

The following figure shows the code of the algorithm in ELENA.

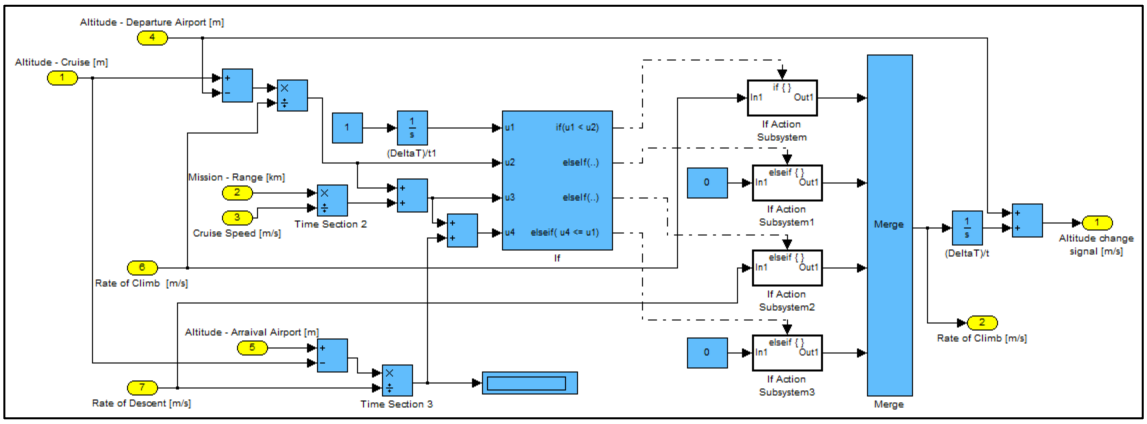


Figure 46: Algorithm for the flight path, designed in ELENA

Once the altitude signal can be generated, the calculations their respective pressure and temperature can be performed.

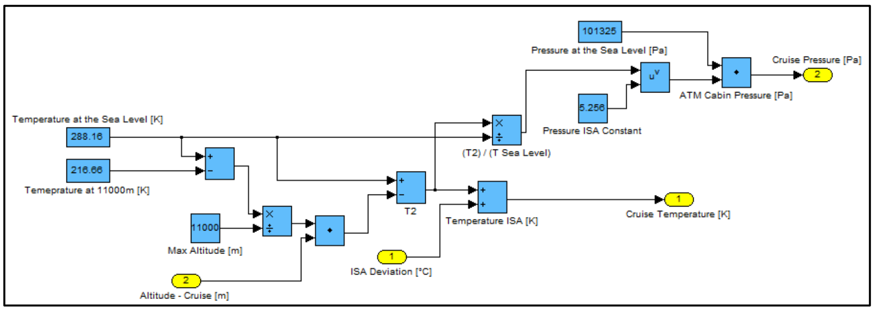
The temperature for the mission profile is given by the following calculations:

$$T_{ATM} = \left[T_{AMSL} - \left(\frac{T_{AMSL} - 216.66}{11000}\right) \cdot h_{ATM}\right] + \Delta T_{ISA}$$

The pressure for the mission profile is given by the following calculations:

$$P_{ATM} = P_{AMSL} \cdot \left(\frac{T_{ATM}}{T_{AMSL}}\right)^{5.256}$$

Hence, the following figure shows the calculations of pressure and temperature for the given altitude signal.



Rate of Climb

This value’s output is the same value’s input.

Departure/Arrival airport values

To perform the further simulations, it is necessary to perform fixed point calculations for the departure and arrival airports; as were performed with the cruise sections. For the departure airport, the temperature and pressure are calculated. For the arrival airport only the pressure is calculated.

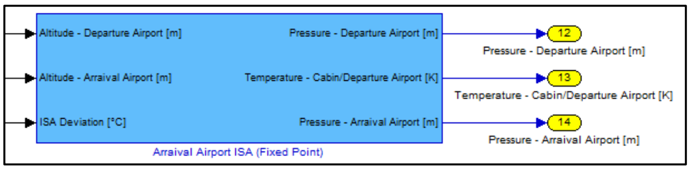


Figure 47: Box for departure/arrival airport in ELENA

Inside the box the following calculations are established.

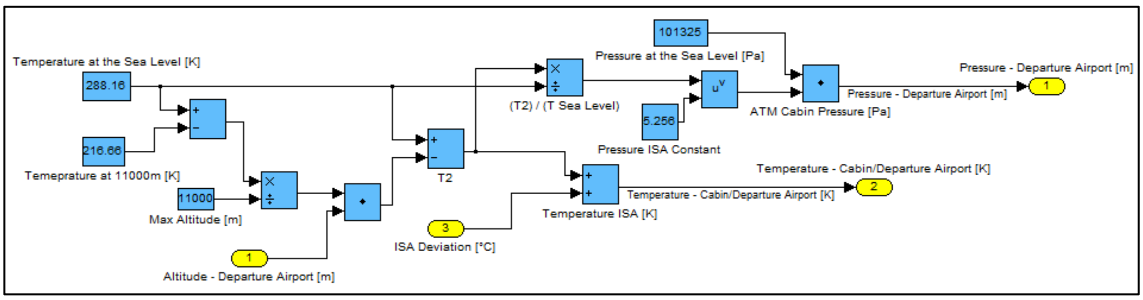


Figure 48: Departure airport calculations in ELENA

Hence, for the departure airport temperature the following calculation has been used.

$$T_{(0)} = \left[T_{AMSL} - \left(\frac{T_{AMSL} - 216.66}{11000}\right) \cdot h_{(0)}\right] + \Delta T_{ISA}$$

For the departure airport pressure the following calculation has been used.

$$P_{(0)} = P_{AMSL} \cdot \left(\frac{T_{(0)}}{T_{AMSL}}\right)^{5.256}$$

For the arrival airport pressure the following calculation has been used.

$$P_{(3)} = P_{AMSL} \cdot \left(\frac{T_{(3)}}{T_{AMSL}}\right)^{5.256}$$

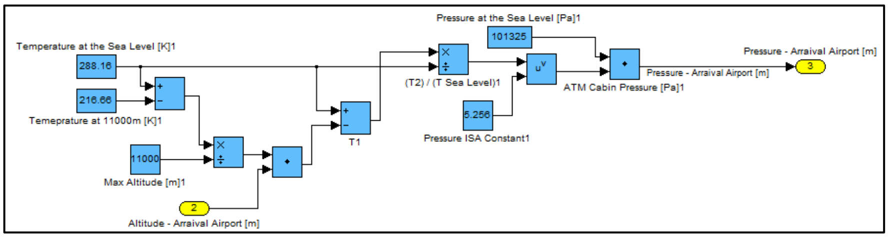


Figure 49: Arrival airport calculations in ELENA

3.6. ELECTRIC ECS CONDITIONING PACK

Design Philosophy and Target

The main purpose of the ECS is to supply a survivable and confortable cabin environment for the passengers, under certain properties such as pressure, temperature and moisture. Those characteristics must be maintained with acceptable limits through the entire mission profile, such mission involves various phases, each one with a particular atmospheric condition.

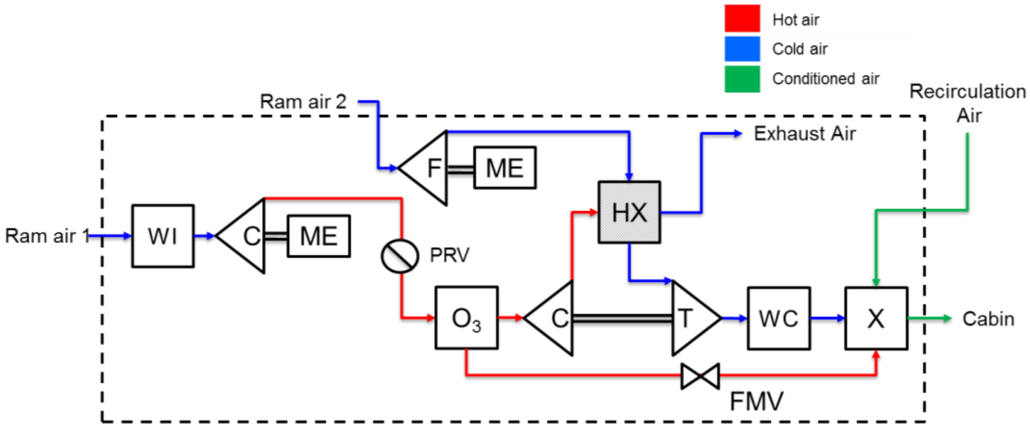
Technical Description

Following innovative concepts to reduce the energy consumption, a no-bleed air ECS is selected. Therefore the main source of energy, the pneumatic power, is eliminated and replaced by electrical power. In this case, the air is taken as ram-air and subsequently is conditioned with the design requirements established by the CS25.

EXPECTED TYPICAL CHARACTERISTICS FOR THE ELECTRIC ECS	
Estimated energy consumption [E]	1.14 kW per passenger
Temperature range for the ECS pack [T]	90°C to -5°C
Cabin temperature range [T]	18°C to 30°C
ECS cabin pressure operation limit [P]	75 kPa or 2440 m AMSL
Security factor for structure design (f_s)	1.5

Table 10: Electric ECS typical components

EXPECTED TYPICALELECTRIC ECS COMPONETNS
• 2 Conditioning Packs:
▪ 1 inertial water separator
▪ 1 compressor + 1 electric motor
▪ 1 pressure reduction valve
▪ Ozone reduction unit
▪ Air Cycle Machine
▪ Heat exchanger +1 fan + 1 electric motor
▪ 1 centrifugal water separator
▪ 1 manifold mixing unit + 1 control valve
• Pipelines
• 1 pressure control outflow valve
• 2 emergency positive-pressure relief valves
• 2 emergency negative-pressure relief valves



C	Compressor	WC	Centrifugal water separator
T	Turbine	HX	Heat exchanger
ME	Electric motor	O_3	Ozone remover
WI	Inertial water separator	X	Manifold for air distribution unit
PRV	Pressure Reduction Valve	F	Fan
FMV	Flow mixing valve		

Figure 50: Electric ECS typical components

Following the expected electric ECS architecture, the following scheme has been designed on ELENA. Some components like ozone separator, water separator and filters are not taken into account, since are considered that do not affect the main analysis results.

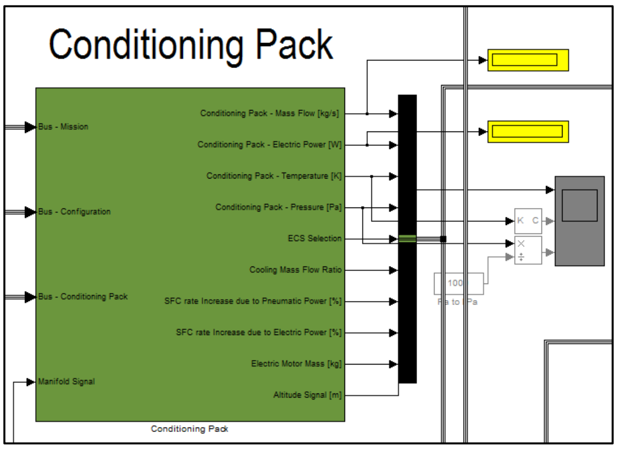


Figure 51: Conditioning Pack Module

As seen on the following figure, the conditioning pack follows the architecture of the expected electric ECS design.

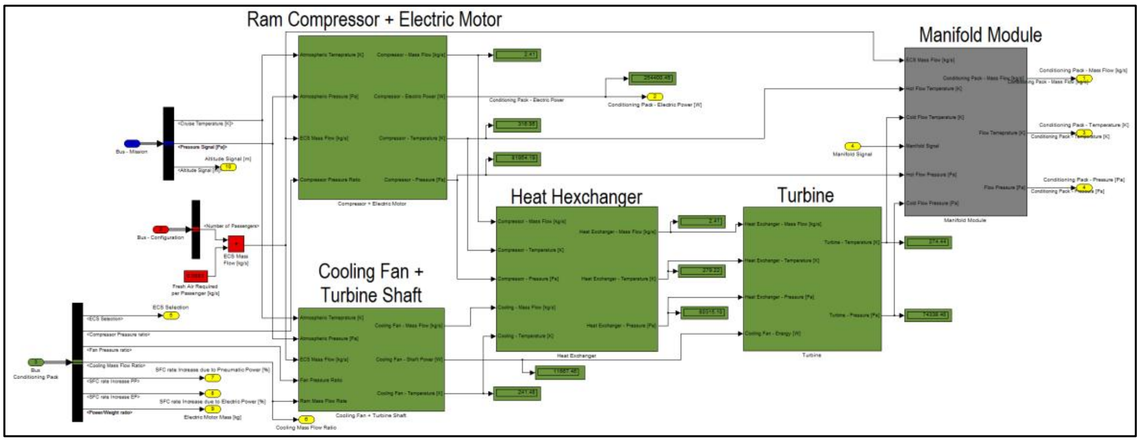


Figure 52: Conditioning pack module in ELENA

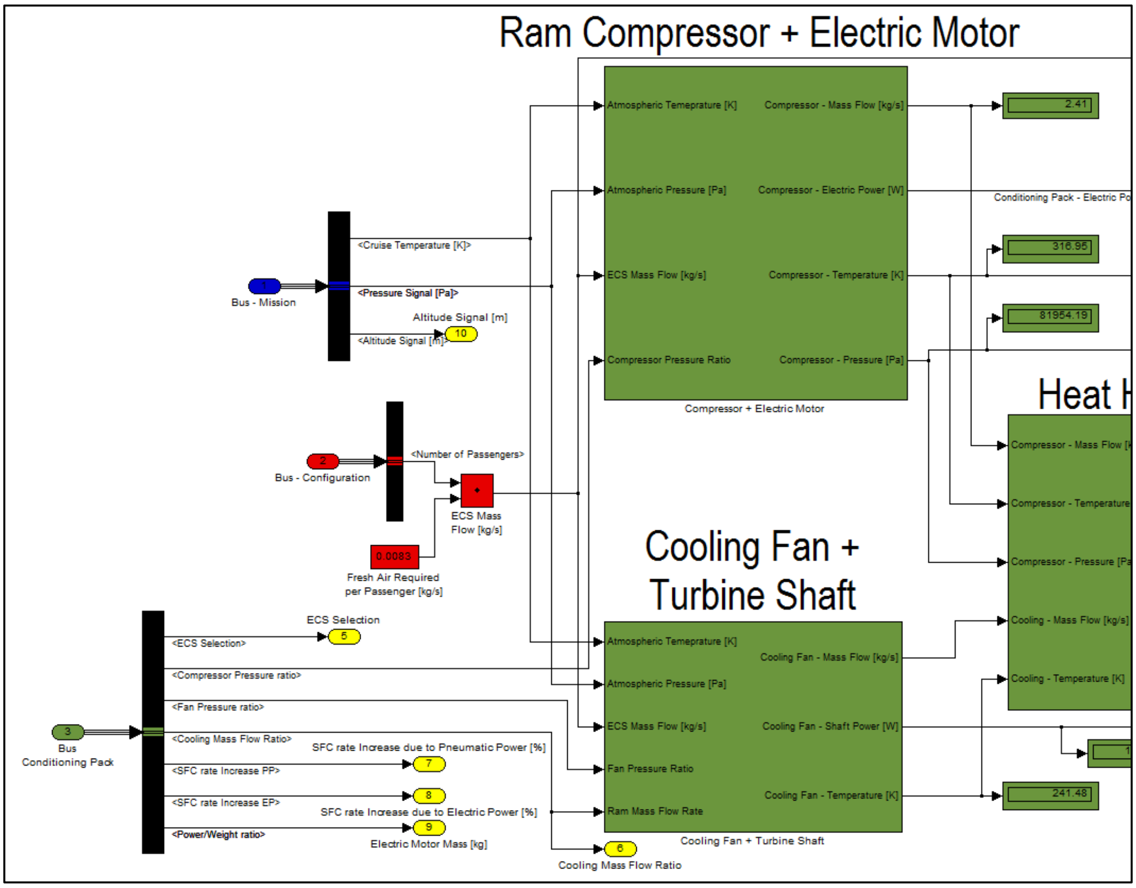


Figure 53: Conditioning pack module in ELENA (Left side)

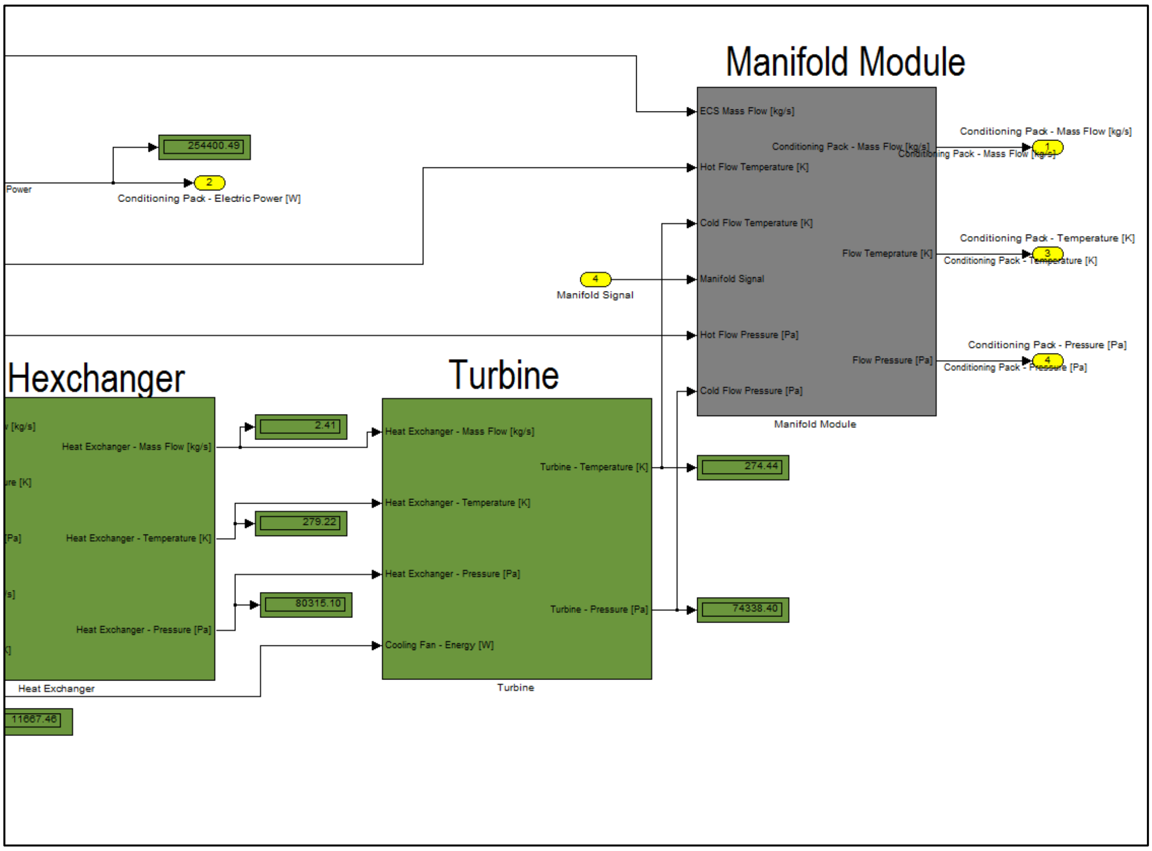


Figure 54: Conditioning pack module in ELENA (Right side)

ECS Conditioning Pack Inputs

Once the previous scheme has been programed in ELENA, a case study can be carried out using the next inputs.

Table 11: Conditioning Pack Configuration Inputs

Input	Units	Optimal Range	Note
1. ECS Selection	-	[1 or 2]	1= Conventional 2= Electrical
2. Compressor Pressure Ratio (Π_c)	-	[0.8 to 0.95]	
3. Fan Pressure Ratio (Π_f)	-	[0.8 to 0.95]	
4. Cooling mass flow ratio (CFR)	-	[0 to 1]	This value represents how much mass flow is used for cooling
5. Power/Weight ratio for an electric motor [PW]	kW/kg	[2 to 10]	
6. SFC rate increase due to Pneumatic Power [ϕ_{SFC}]	Ratio	[0 to 1]	0=0% 1=100%
7. SFC Increase due to Electric Power [ϕ_{SFC}]	Ratio	[0 to 1]	0=0% 1=100%

Conditioning Pack Outputs

For aircraft with passengers, the minimum air flow requirement is established by the rules CS25 and CS29. On the other hand; for design purposes of modern aircraft a bigger [10]value is taken to improve passenger comfort and to have an acceptable range of flow in real operation. Hence, the following calculations are taken into account.

The mass flow for the ECS is given by the following calculations:

$$\dot{m}_{ECS} = PAX \cdot \dot{m}_{per\ PAX}$$

Where,

$$\dot{m}_{per\ PAX} = 0.00833\ kg/s$$

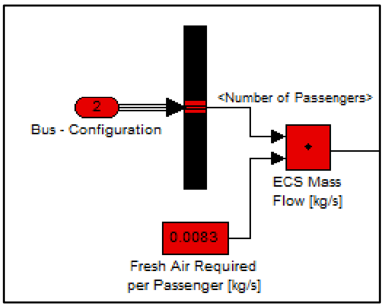


Figure 55: ECS flow requirement in ELENA

Compressor

[10]Thermo-gas dynamic calculations have been taken into account for compressor and fan calculations.

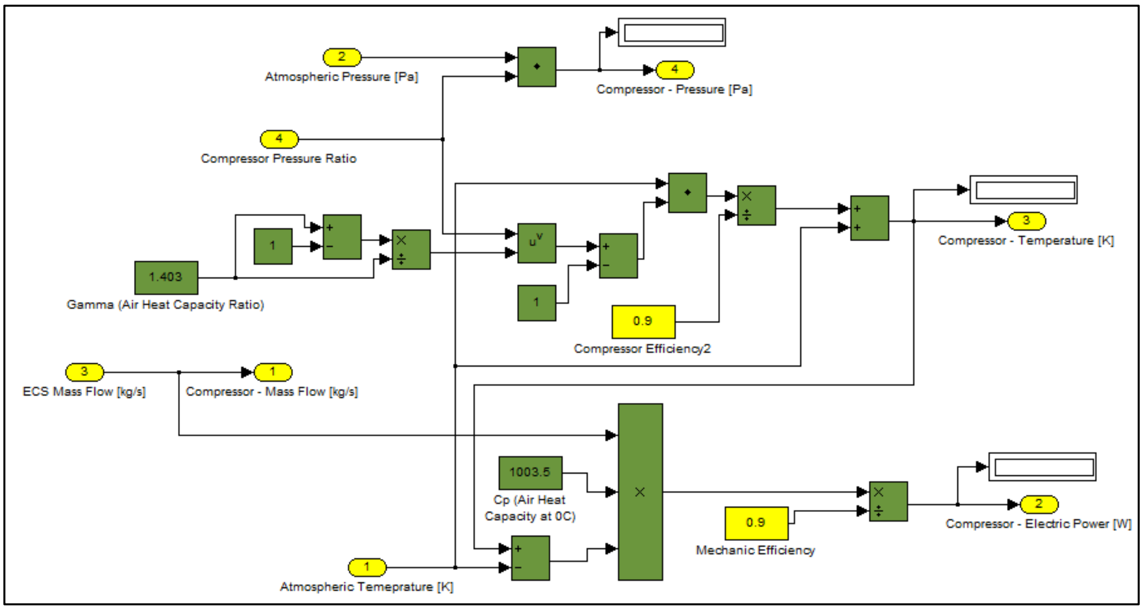


Figure 56: Air Cycle Machine - Compressor calculations in ELENA

The mass flow for the compressor is given by the following calculations:

$$\dot{m}_c = \dot{m}_{ECS}$$

The temperature for the compressor is given by the following calculations:

$$T_c = \frac{T_{ATM}}{\eta_c} \cdot \left[\Pi_c{}^{\left(\gamma-1/\gamma\right)} - 1 \right] + T_{ATM}$$

Where,

$$\eta_c \sim 0.9$$

$$\gamma \sim 1.4$$

The pressure for the compressor is given by the following calculations:

$$P_c = \Pi_c \cdot P_{ATM}$$

The electric power for the compressor is given by the following calculations:

$$EPW_c = \dot{\mathrm{m}}_{ECS} * Cp_{air} * (T_c - T_{ATM})$$

Where,

$$Cp_{air} = 1003.5\, J/(kg \cdot K\}$$

Fan

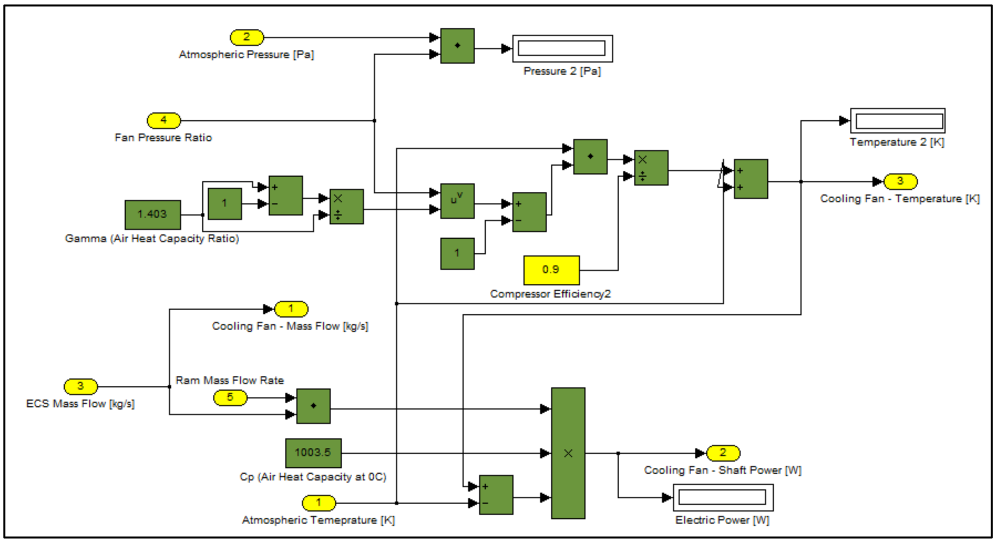


Figure 57: Air Cycle Machine - Fan calculations in ELENA

The mass flow for the fan is given by the following calculations:

$$\dot{m}_f = \dot{m}_{ECS} \cdot CFR$$

The temperature for the fan is given by the following calculations:

$$T_f = \frac{T_{ATM}}{\eta_f} \cdot \left[\Pi_f^{\left(\gamma-1/\gamma\right)} - 1 \right] + T_{ATM}$$

Where,

$$\eta_f \sim 0.9$$

$$\gamma \sim 1.4$$

The pressure for the fan is given by the following calculations:

$$P_f = \Pi_f \cdot P_{ATM}$$

The shaft power for the fan is given by the following calculations:

$$SPW_f = \dot{m}_f * Cp_{air} * \left(T_f - T_{ATM}\right)$$

Where,

$$Cp_{air} = 1003.5\, J/(kg \cdot K\}$$

Heat Exchanger

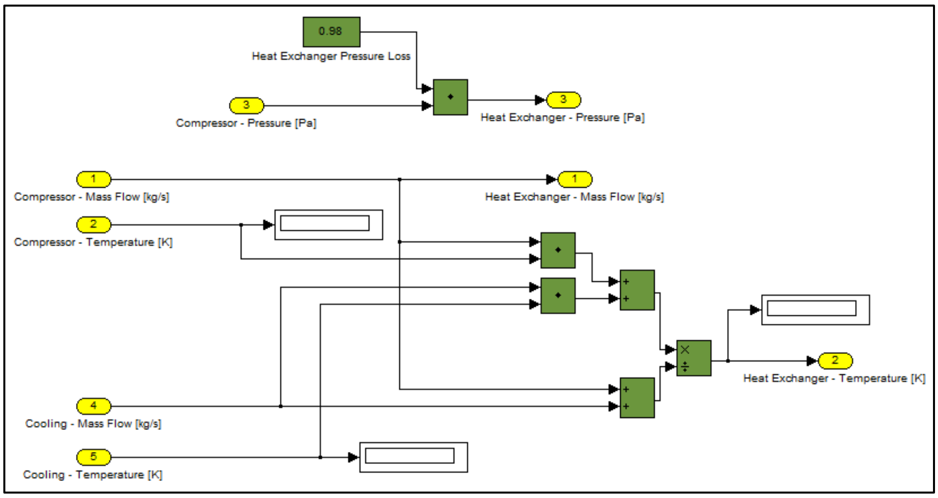


Figure 58: Air Cycle Machine - Heat exchanger calculations for ELENA

The mass flow for the heat exchanger is given by the following calculations:

$$\dot{m}_{hx} = \dot{m}_c$$

The temperature for the heat exchanger is given by the following calculations:

$$T_{hx} = \frac{\dot{m}_{hx} \cdot T_c + \dot{m}_f \cdot T_f}{\dot{m}_{hx} + \dot{m}_f}$$

The pressure drop for the heat exchanger is given by the following calculations:

$$P_{hx} = \varepsilon_{hx} \cdot P_c$$

Where,

$$\varepsilon_{hx} {\sim} 0.98$$

Turbine

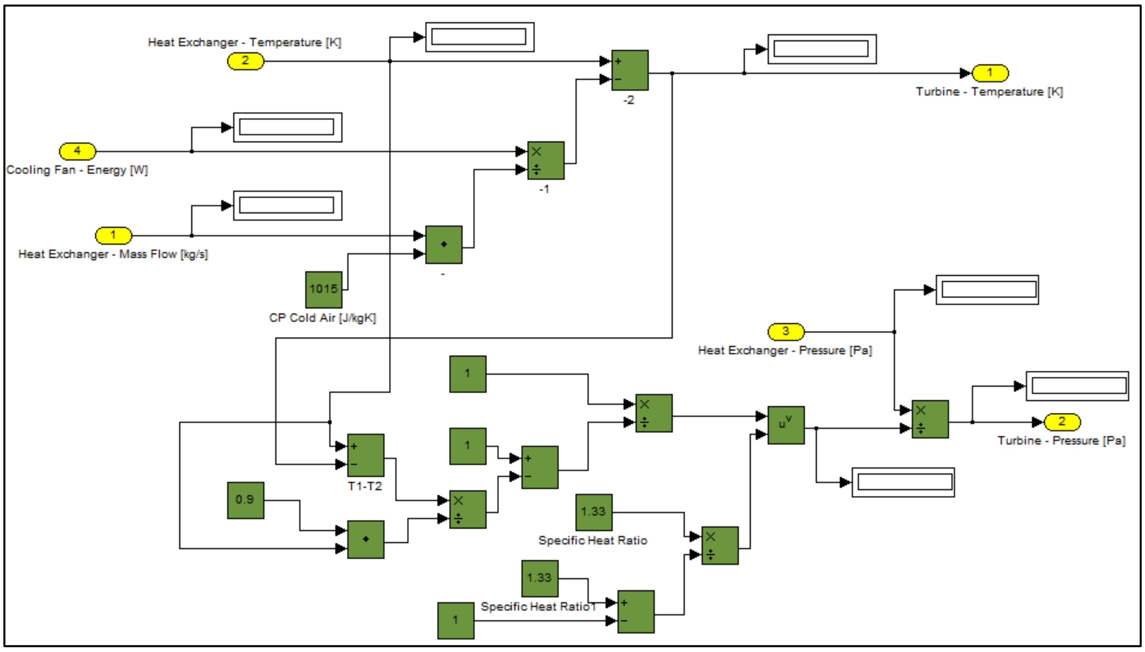


Figure 59: Air Cycle Machine - Turbine calculations for ELENA

The mass flow for the turbine is given by the following calculations:

$$\dot{m}_t = \dot{m}_{hx}$$

The temperature for the turbine is given by the following calculations:

$$T_t = T_{hx} - \frac{SPW_f}{\dot{m}_{hx} \cdot Cp_{air}}$$

The pressure for the turbine is given by the following calculations:

$$P_t = \frac{P_{hx}}{\left(\dfrac{1}{1 - \dfrac{T_{hx} - T_t}{\eta_t \cdot T_{hx}}}\right)^{\frac{\gamma}{\gamma - 1}}}$$

Where,

$$\eta_t \sim 0.9$$

$$\gamma \sim 1.4$$

Manifold

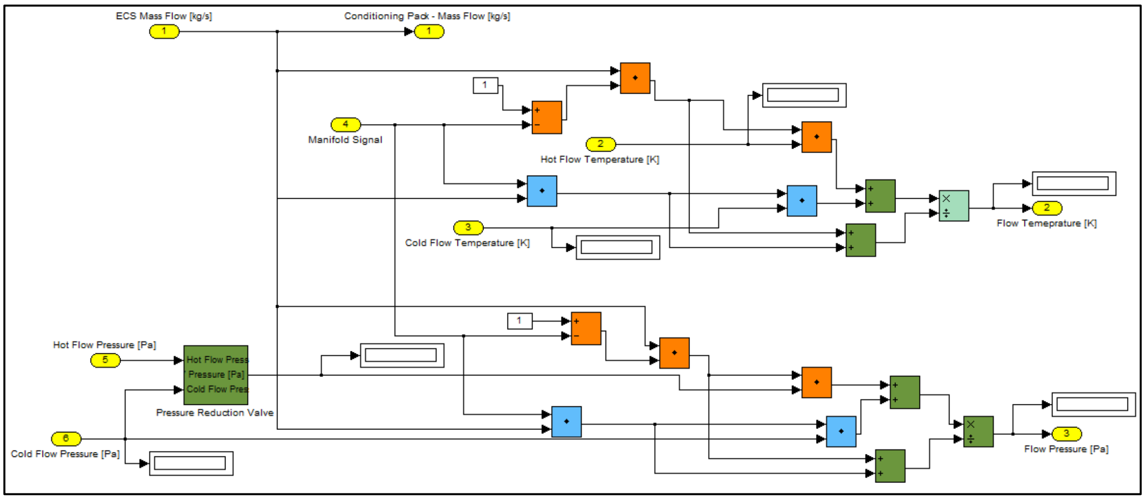


Figure 60: Air Cycle Machine - Manifold calculations for ELENA

The mass flow for the manifold is given by the following calculations:

$$\dot{m}_{mf} = \dot{m}_{ECS}$$

The temperature for the manifold is given by the following calculations:

$$T_{mf} = \frac{\dot{m}_t \cdot T_t + \dot{m}_c \cdot T_c}{\dot{m}_t + \dot{m}_c}$$

The pressure for the manifold is given by the following calculations:

$$P_{mf} = \frac{\dot{m}_t \cdot P_t + \dot{m}_c \cdot P_{PRV}}{\dot{m}_t + \dot{m}_c}$$

Where,

$$P_{PDV} = P_c \cdot \frac{P_t}{P_c}$$

ECS Selection Signal

The ECS selection signal gives a command for perform calculations on conventional or electric models.

SFC rate increase due to Pneumatic and Electric Powers

At this point, depending if it is a conventional or electric ECS's analysis; the required pneumatic and electric energies are calculated for this particular aircraft. For the next task it is necessary to use a performance simulation tool. Turbomatch and Gasturb were used for this research; where basically the engine is simulated to assess the increment on the Specific Fuel Consumption due to the power-off take extraction. Subsequently this increment percentage in SFC is used in ELENA. Hence, the fuel penalty is assessed in conjunction with other parameters; such as the system drag and system mass contribution. The inputs used for this research are described in the Chapter 2.20.

From the basic proportions method, the SFC increase rate is calculated using the following procedure.

$$SFCR_{ECS} = \frac{SFC_{(with\ pneumatic\ energy\ extraction)}}{SFC_{(no\ energy\ extraction)}} - 1$$

The same procedure is applied for the electric ECS

$$SFCR_{EECS} = \frac{SFC_{(with\ electri\ energy\ extraction)}}{SFC_{(no\ energy\ extraction)}} - 1$$

3.7. CABIN SIMULATION CALCULATIONS

Those calculations aim to simulate the cabin temperature and pressurization. Hence, the response of the configured conditioning pack for a mission profile can be analysed. The mission profile includes the three main flight phases, climbing, cruise and a descent.

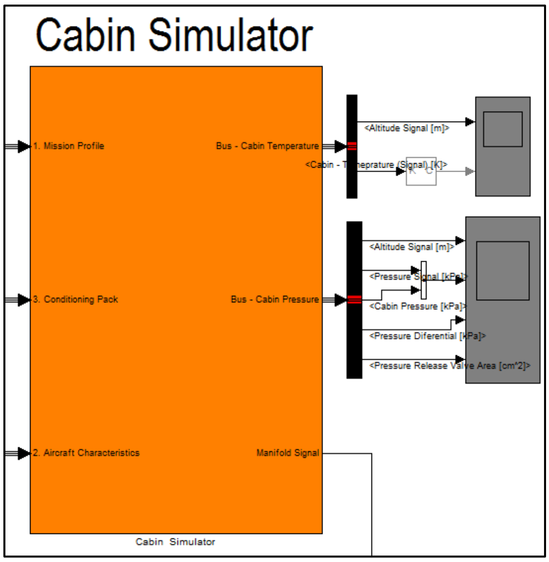


Figure 61: Cabin simulator module in ELENA

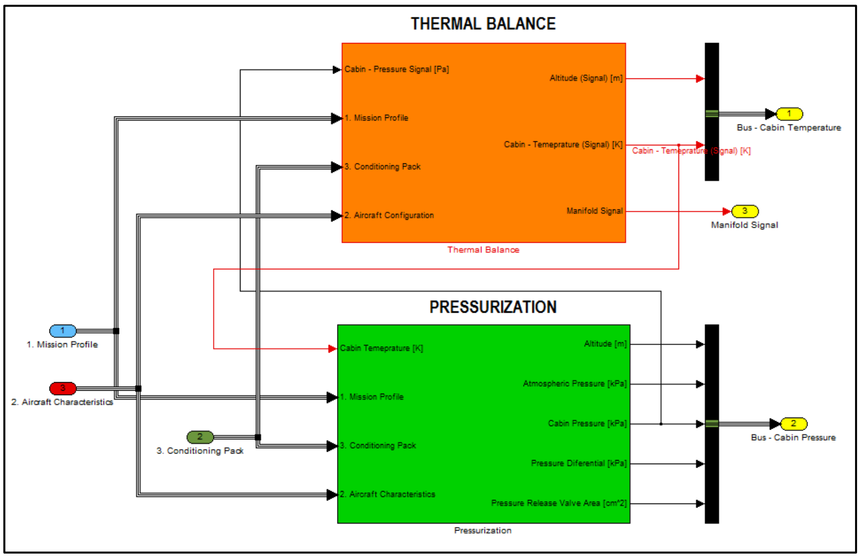


Figure 62: Content of the module for simulation

Thermal Balance

The calculations of the thermal balance analyse the temperature behaviour through the time under 4 main conditions or heat contributors; such conditions are the solar radiation, heat produced by passengers, atmosphere temperature and air ventilation for cabin temperature regulation. For the cabin volume, only the air occupying this space is considered. Other components which occupy volume and affect the internal energy distribution, such as chairs or utility equipment were not considered since they didn't represent a relevant change for the final results.

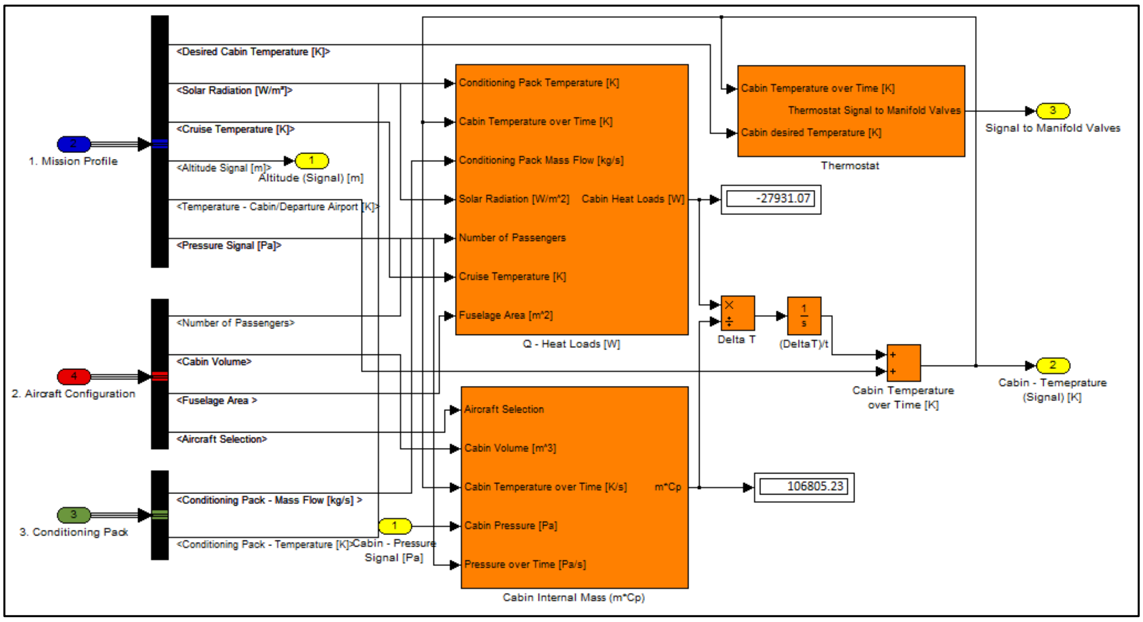


Figure 63: Calculations for the thermal balance inside ELENA

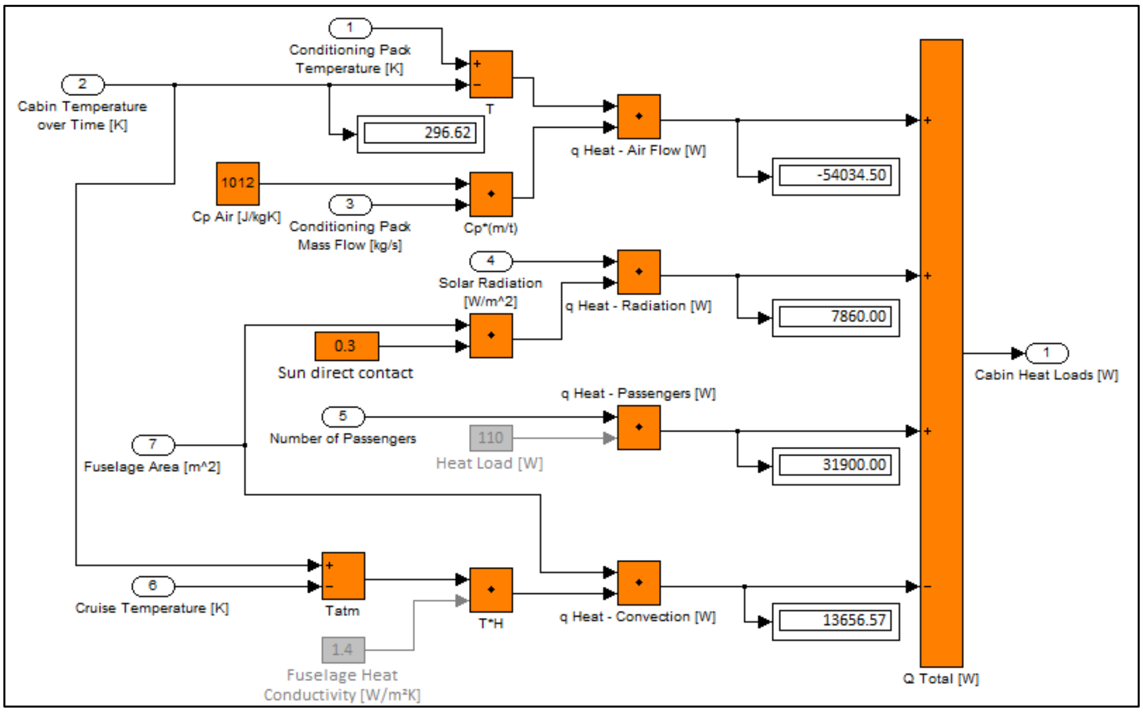


Figure 64: Heat loads

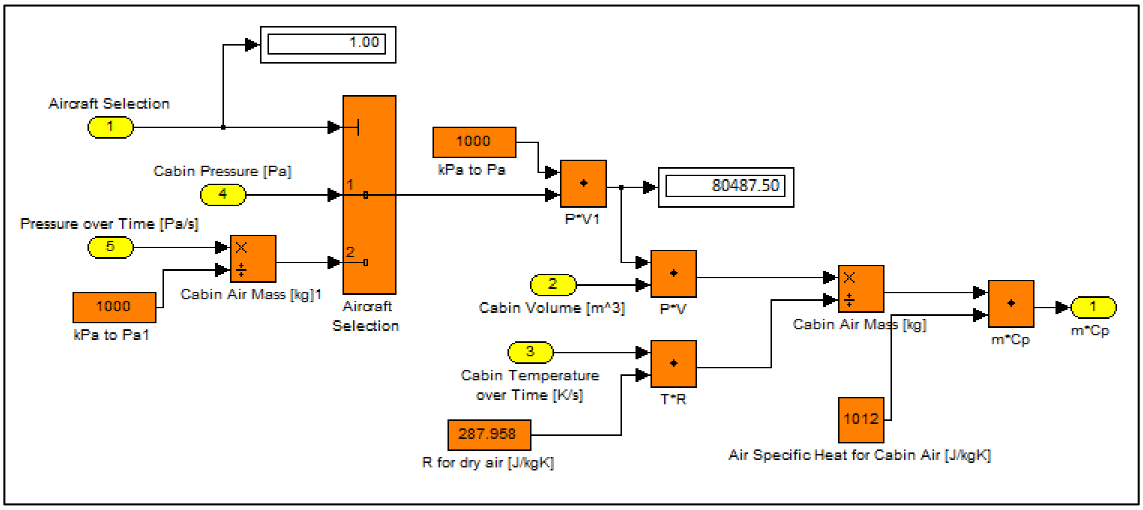


Figure 65: Internal volume energy

Hence, the cabin temperature for the thermal balance is given by the following calculations, which have been derived from the first law of thermodynamics. For this thermal balance calculation, only the cabin air mass is considered, since the furnishing become more complex the analysis and is not relevant enough for the final result.

$$T_{cab} = T_0 + \frac{\partial T_{cab}}{t}$$

Where,

$$\frac{\partial T_{cab}}{t} = \frac{q_{\dot{m}} + q_s + q_p + q_c}{Cp_{air} \cdot \frac{\left(P_0 + \frac{\partial P_{cab}}{t}\right) \cdot V_{cab}}{T_{cab} \cdot R}}$$

$$q_{\dot{m}} = \dot{m}_{mf} \cdot Cp_{air} \cdot \left(T_{mf} - T_{cab}\right)$$

$$\dot{m}_{mf} = \dot{m}_{ECS}$$

$$q_{sr} = \sigma_{sr} \cdot A_{sr} \cdot 0.3$$

$$q_p = q_{pp} \cdot PAX$$

$$q_c = \tau_{sr} \cdot A_{sr} \cdot (T_{cab} - T_{ATM})$$

$$\frac{\partial T_{cab}}{t} = \frac{\dot{m}_{mf} \cdot Cp_{air} \cdot \left(T_{mf} - T_{cab}\right) + \sigma_s \cdot A_{sr} \cdot 0.3 + q_{pp} \cdot PAX + \tau_{sr} \cdot A_{sr} \cdot (T_{cab} - T_{ATM})}{Cp_{air} \cdot \frac{\left(P_0 + \frac{\partial P_{cab}}{t}\right) \cdot V_{cab}}{T_{cab} \cdot R}}$$

The regulation of the cabin temperature is achieved in the manifold with the mixture of the cold ($\dot{m}_t$) and hot ($\dot{m}_c$)flow. This mixture is regulated through a thermostat system which mainly calculates the difference between the current temperature and the desired temperature. Hence; if this temperature difference shows that the cabin temperature is higher than the desired one, then a signal closes the valve of the hot($\dot{m}_c$) flow in the manifold section. Otherwise if the temperature is below the desired the signal opens this valve. The maximum tolerance range for this temperature difference was programed as 2° C. This automatic control was done with a pre-configured command in Simulink which sends a signal of 0 or 1, in terms of a condition.

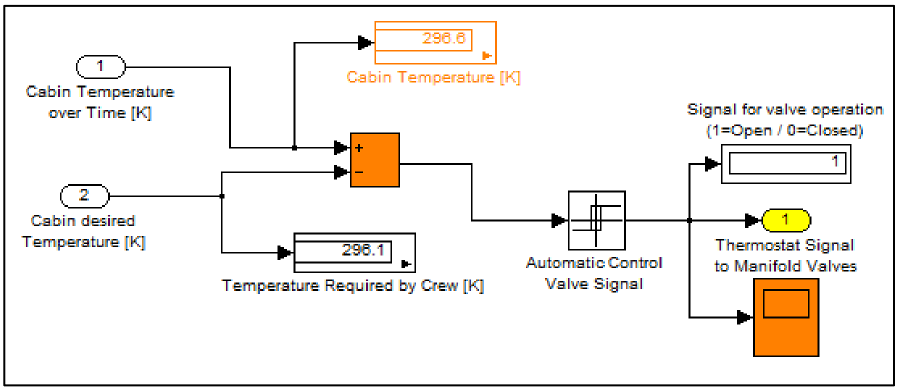


Figure 66: Strategy to regulate the cabin temperature

As the previous image shows; in that case the desired temperature for the cabin is 293.1 K. The cabin temperature with the thermal balance is 294.3 K which is above my requirement or hotter. Therefore, the Automatic Control Valve Signal sends a signal to close the valve of the Hot Flow $(\dot{m}_c)$ in the manifold section.

Pressure Module

As mentioned previously; the main purpose of the pressurization is to provide acceptable levels of oxygen for the passengers and crew. Hence, the following requirement must be accomplished for the ECS.

Acceptable pressure levels for at least 75 kPa or the equivalent for an altitude of 2400 m above the main sea level. This value represents a pressure differential of around 50 kPa. Major values for a better cabin air quality, higher than 75 kPa, can be achieved on the cabin pressurization.

In real operation, this requirement is achieved through the control unit, which mainly operates a Pressure Release Valve. Hence; for this research, an algorithm which is restrained with this requirement, has been designed.

The following figure shows the box which performs the pressurization calculation. The Cabin Pressurization box simulates the cabin pressurization through an algorithm, which is similar to those ones that can be found on real control units for ECS operation. The Rate of Pressurization box performs calculations for the flow that is coming from the conditioning pack; this calculation is fundamental since it affects the overall pressurization depending on the air pack characteristics. The Pressure Release Valve

Area box performs calculations to establish the operation of the PRV through the entire mission.

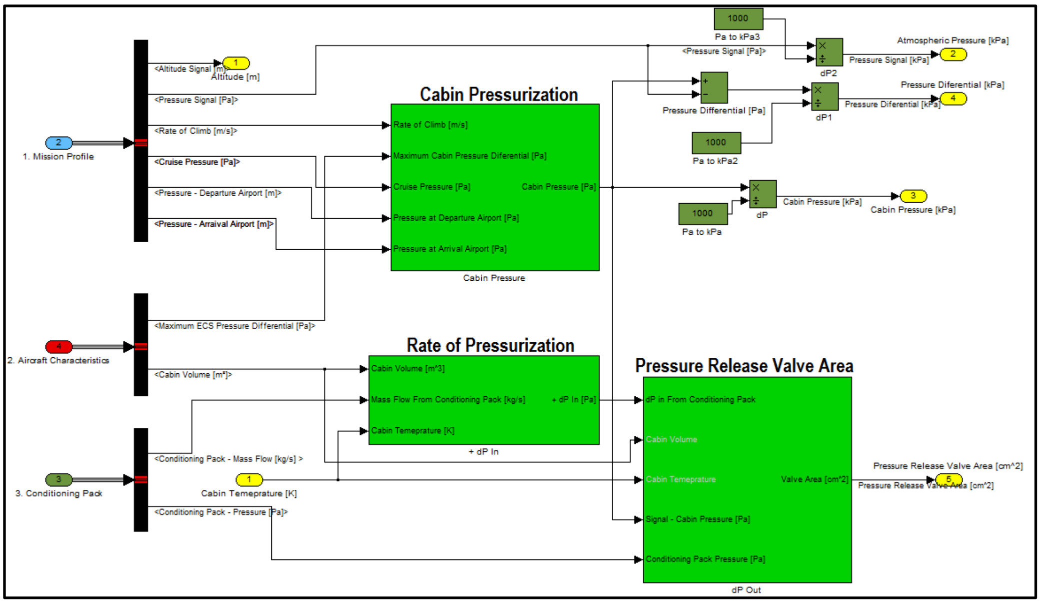


Figure 67: Calculations for pressurization in ELENA

The following figure shows the box containing the code for the pressurization.

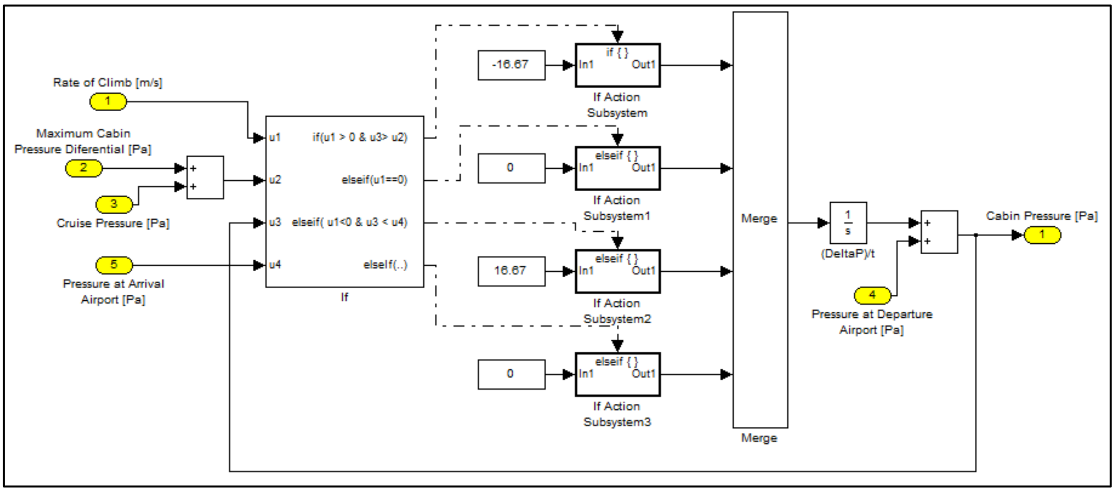


Figure 68: Pressurization box in ELENA

Hence, the pressure for the cabin is given by the following calculations:

$$P_{cab} = P_0 + \frac{\partial P_{cab}}{t}$$

Where,

$$IF \quad \frac{\partial vs}{t} > 0 \quad AND \quad P_{cab} > (\Delta P_{max} + P_{ATM}) \quad THEN \quad \frac{\partial P_{cab}}{t} = -16.67\ Pa$$

$$IF \quad \frac{\partial vs}{t} = 0 \quad THEN \quad \frac{\partial P_{cab}}{t} = 0$$

$$IF \quad \frac{\partial vs}{t} < 0 \quad AND \quad P_{cab} < P_3 \quad THEN \quad \frac{\partial P_{cab}}{t} = 16.67\ Pa$$

$$IF \quad NON\ OF\ ABOVE \quad THEN \quad \frac{\partial P_{cab}}{t} = 0$$

The pressure differential between the cabin and the atmosphere is given by the following calculations:

$$\Delta P = P_{cab} - P_{ATM}$$

The rate of pressure entering to the aircraft cabin is given by the following calculations:

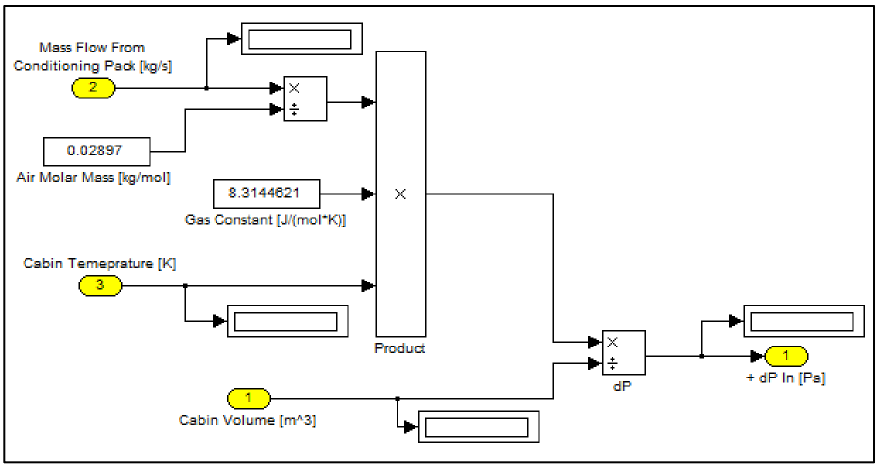


Figure 69: Rate of pressure entering in the aircraft cabin

$$dP_{mf} = \frac{\frac{\dot{m}_{mf}}{M_{air}} \cdot R \cdot T_{cab}}{V_{cab}}$$

Where,

$$M_{air} = 0.02897\ kg/mol$$

$$R = 8.314\ J/(K \cdot mol)$$

The following calculations were performed to establish the operation of the Pressure Release Valve. Basically those calculations give the required area of aperture for this valve to achieve the requirements of pressurization.

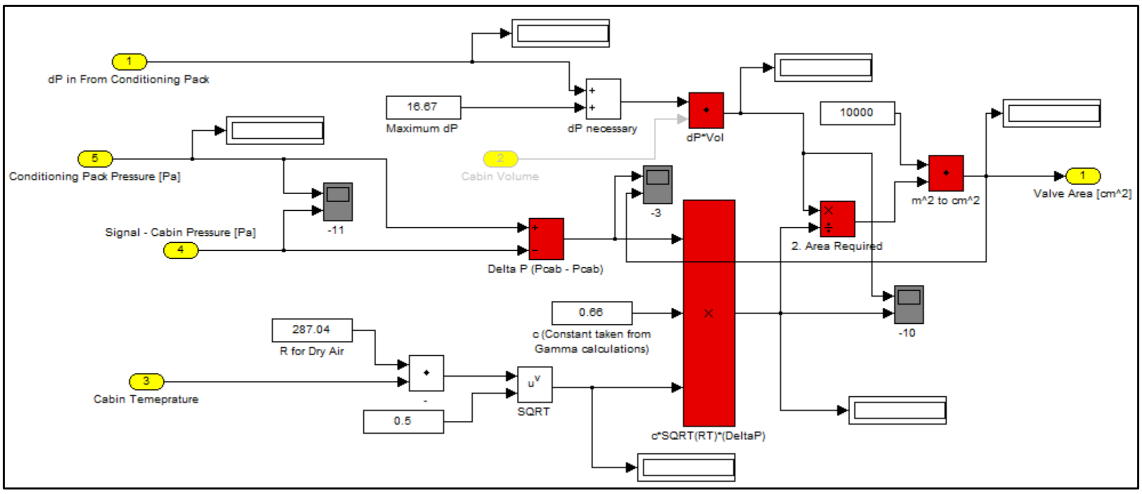


Figure 70: Calculations for the Pressure Release Valve Area in ELENA

Hence, the Pressure Release Valve area for the pressurization is given by the following calculations:

$$A_{PRV} = \frac{\left(dP_{mf} + dP_{max}\right) \cdot V}{\left[\gamma^{\frac{1}{2}} \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2\cdot(\gamma+1)}}\right] \cdot \sqrt{R_{air} \cdot T_{cab}} \cdot (P_{cab} - P_{ATM})}$$

Where,

$$dP_{max} = 16.67\ Pa = maximum\ rate\ of\ pressurization$$

$$\gamma \sim 1.4$$

$$R_{air} = 287.04$$

3.8. FUEL PENALTY CALCULATIONS

The fuel penalties are assessed in terms of fuel flow due power-off take, system drag and system weight. Those calculations were taken from the method presented in the section 2.13

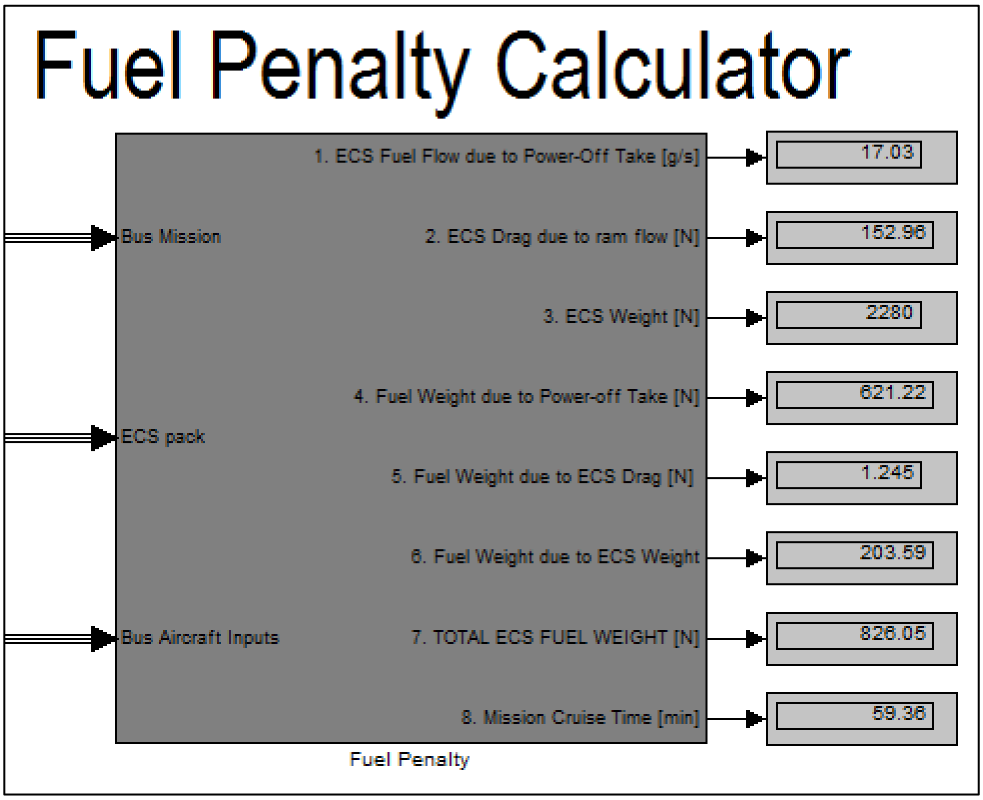


Figure 71: Fuel Penalty Module for ELENA

The following figure shows the content of the module for Fuel Penalty.

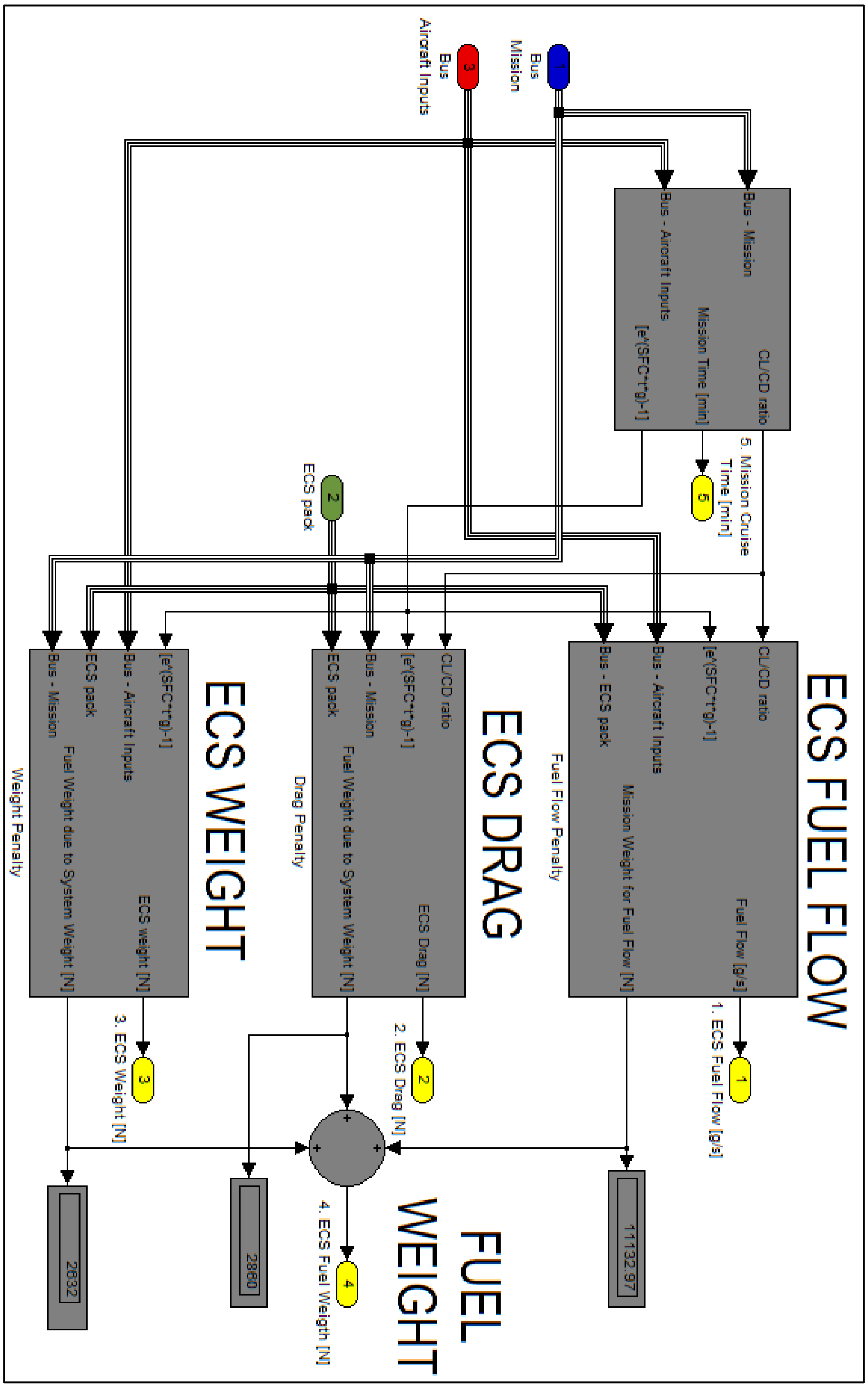


Figure 72: Energy penalties calculations in ELENA

ECS Fuel Flow Penalties

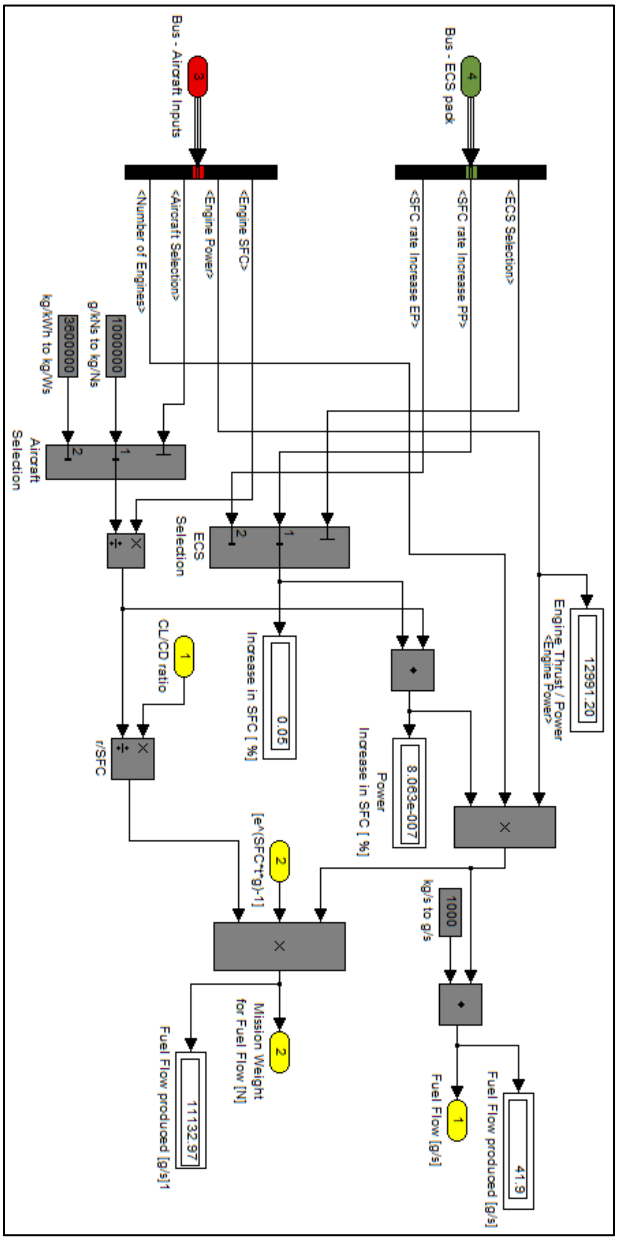


Figure 73: Fuel penalties calculations due to power-off take

The ECS fuel penalty for the energy impact is given by the following calculations taken from the method presented in the section 2.13. Firstly the fuel flow due power-off take is calculated.

$$FW_{ECS} = FN \cdot EN \cdot SFC \cdot \phi_{SFC}$$

Where,

$$FN = Net\,Thrust = PW = Net\,Shaft\,Power$$

$$EN = (Number\ of\ engines)$$

$$\phi_{SFC} = Fuel\,increase\,rate$$

The fuel increment rate is taken form the analysis in the Engine Performance Simulation Tools. Now the weight due power-off take is calculated.

Hence

$$WF_{FW} = FW_{ECS} \cdot \left(e^{\frac{SFC \cdot t \cdot g}{r}} - 1\right) \cdot \frac{r_{L/D}}{SFC}$$

Where,

$$g = 9.81 \frac{m}{s^2} = AMSL\ gravity$$

$$r_{L/D} = \frac{W_{AAM}}{D}$$

$$W_{AAM} = (m_{AUM} - 0.4 \cdot m_{FDM}) \cdot g$$

$$D = FN \cdot NE$$

ECS Drag Penalties

Continuing with the procedure, the ECS drag penalties are calculated through the following interface in ELENA.

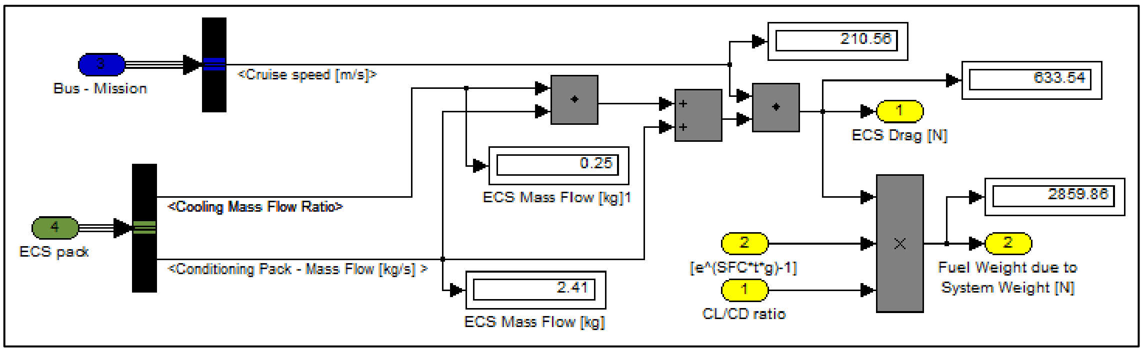


Figure 74: Aircraft performance calculations

Where the ECS drag penalty is derived with the following equation:

$$FD_{ECS} = \dot{m}_{ECS} \cdot CFR \cdot v_{(1-2)} + \dot{m}_{ECS} \cdot v_{(1-2)}$$

Where,

$$CFR = Cooling\ Flow\ Ratio$$

The cooling flow ratio defines the amount of mass flow to be used for cooling the main mass flow. Hence, if the required ECS mass flow is 1.8 kg/s and the CRF is 0.5 then the flow required for cooling will be 0.9 kg/s.

Now the weight due the drag generated by the system is derived with the following equation.

$$WF_{FD} = FD_{ECS} \cdot \left(e^{\frac{SFC \cdot t \cdot g}{r}} - 1\right) \cdot r_{L/D}$$

ECS Weight Penalties

Since the electric ECS has further components, a study has been perform to analyse how those extra components would affect the electric ECS weight in comparison with the conventional ECS. Hence, the following table was developed.

Table 12: Difference in components for the electric and conventional ECS's

Component	Conventional ECS	Electric ECS	Note
Compressor for the ram air		✓	Is estimated, based in the mass of a titanium disc with the area required to ram the required cabin air flow.
Electric motor		✓	Is estimated though the power to weight ratio of an electric motor capable to supply 120 kW
Wiring to run the electric motor		✓	Offset by the pipelines of the conventional ECS
Engine electric generator		✓	Is estimated using the same method for the electric motor
Piping from the engine	✓		Offset by the extra wiring of the electric ECS

Hence, from the previous study the mass penalty produced by the electric ECS is calculated using the procedure for conventional ECS plus the addition of the following weights; motor, engine electric generator impact and compressor. The weight of the extra wiring that comes from the engine to supply electric power to the ECS is offset by elimination of pipelines that, in the same way, would come from the engine to provide pneumatic power to the ECS conditioning packs.

Hence, the calculations inside ELENA have been programed in the following way.

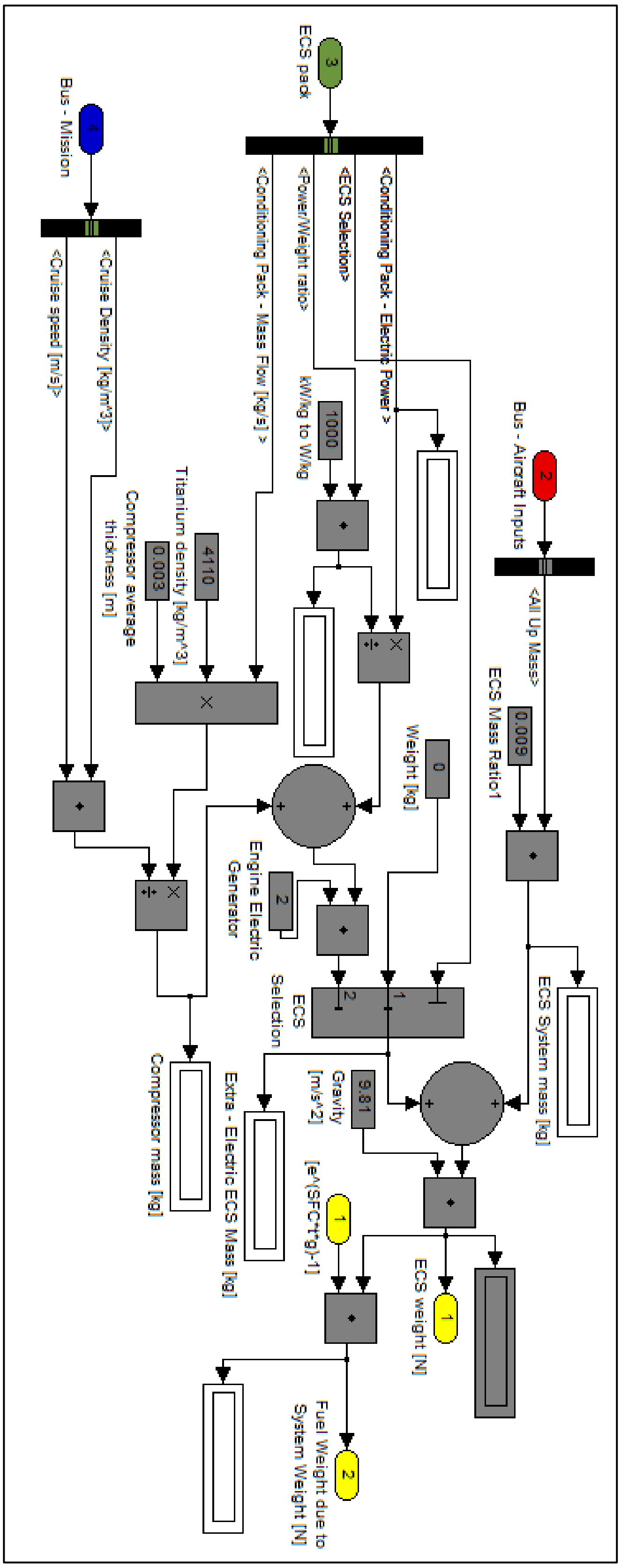


Figure 75: System weight penalty in ELENA

The conventional ECS weight for the mass penalty is given by the following calculations:

$$W_{CECS=}m_{CECS} \cdot g$$

Where,

$$m_{CECS} = 0.009 \cdot m_{AUP}$$

The electric ECS mass for the mass penalty is given by the following calculations. To calculate the mass contribution of the electric motors, a [19]power-to-weight ratio term has been used. Following the requirements of the electric ECS electric motors and in reference to the electric motor Hi-Pa Drive HPD40, which can generate up to 120 kW, this value for power-to-weight is considered as “4.8 kW/kg”. This value is multiplied by 2 since represents the mass of both, the electric motor and the extra mass for the engine electric generator.

$$W_{EECS=}\left(m_{CECS} + 2 \cdot m_{motor} + m_{compressor}\right) \cdot g$$

Where,

$$m_{CECS} = 0.009 \cdot m_{AUP}$$

$$m_{motor} = \frac{EPW_c}{P/W_{EM}}$$

$$m_{compressor} = \rho_{Titanium} \cdot A_{ECS\,Flow} \cdot h_{disc\,width}$$

$$A_{ECS\,Flow} = \frac{\dot{\mathrm{m}}_{ECS}}{\rho_{(1-2)} \cdot v_{(1-2)}}$$

$$WF_W = W_{EECS} \cdot \left(e^{\frac{SFC \cdot t \cdot g}{r}} - 1\right)$$

ECS Total Fuel Weight for the Mission

In conclusion; for the total weight penalty due the impact on the system power-off take, system grad and its own weight, the following equation is used.

$$\sum WF = WF_{FW} + WF_{FD} + WF_W$$

Where,

$$WF_{FW} = (Fuel\ weight\ due\ to\ fuel\ flow)$$

$$WF_{FD} = (Fuel\ weight\ due\ to\ drag)$$

$$WF_{W} = (Fuel\ weight\ due\ to\ system\ weight)$$

3.9. FUEL PENALTY FOR A COMBUSTION HEATER

Only for rotary-wing purposes, a combustion heater has been analysed using the following calculations.

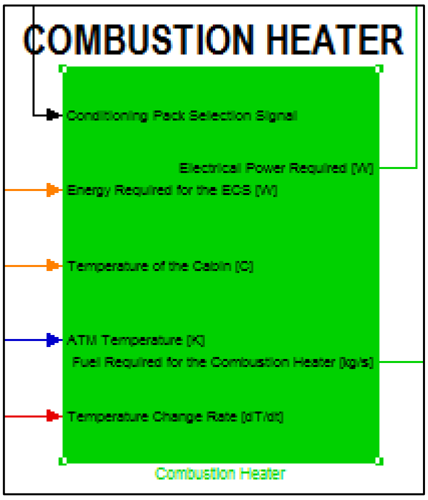


Figure 76: Combustion heater module on a first-stage model version

The following figure was generated to integrate different equations and simulate a combustion heater.

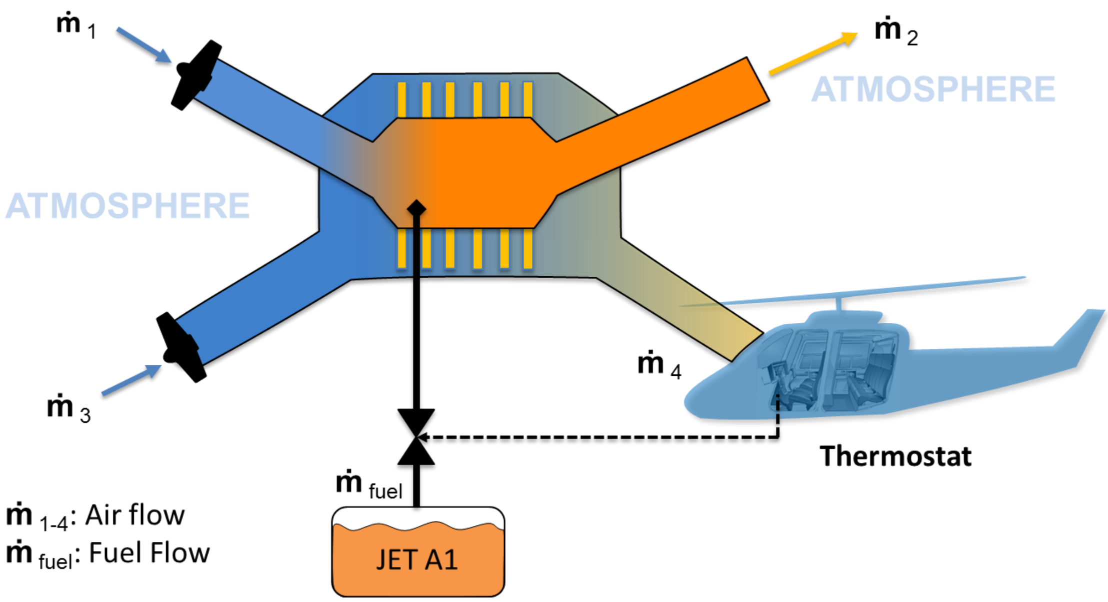


Figure 77: Combustion heater scheme

Hence, the temperature after fan zone 3 is given with the following calculations.

$$T_{out1} = \frac{T_{ATM}}{\eta_{fan1}} * \left[\Pi_{fan1}{}^{\left(\gamma-1/\gamma\right)} - 1 \right] + T_{ATM}$$

The power consumed by the fan in the hot zone is given with the following calculations.

$$w_{fan1} = \dot{m}_1 * C_P * (T_{ATM} - T_1)$$

The Input temperature in the cold zone after the fan is given with the following calculations.

$$T_3 = \frac{T_{ATM}}{\eta_{fan3}} * \left[\Pi_{fan\,3}{}^{\left(\gamma-1/\gamma\right)} - 1 \right] + T_{ATM}$$

The power consumed by the fan in the cold zone is given with the following calculations.

$$w_{fan3} = \dot{m}_3 * C_P * (T_{ATM} - T_3)$$

The Fuel Air Ratio required for the combustion process is given with the following calculations.

$$FAR = \frac{C_{P\,hot} \cdot (T_2 - T_1)}{ETA \cdot FHV}$$

The Fuel flow for the combustion process is given with the following calculations.

$$WF = \frac{CP_{Hot\ Air} \cdot (T_{H2} - T_{H1})}{\eta_{combustion} \cdot FHV} \cdot \dot{m}_1$$

The output temperature in the hot zone after the combustion is given with the following calculations.

1

$$T_2 = \frac{\dot{m}_{fuel} \cdot ETA \cdot FHV}{C_{P\,hot} \cdot \dot{m}_1} + T_1$$

The output temperature after the heat transfer process is given with the following calculations. This temperature is going into the cabin and is given with the following calculations.

$$T_4 = \frac{\dot{m}_1 \cdot C_{P\,hot} \cdot (T_2 - T_1\,)}{\dot{m}_3 \cdot C_P} + T_3$$

Where,

$$\dot{m}_3 \cdot C_P \cdot (T_4 - T_3) = \dot{m}_1 \cdot C_{P\,hot} \cdot (T_2 - T_1\,)$$

3.10. MODEL SPECIFICATIONS

The final model was developed under the next interface.

Table 13: ECS model interface

File Name	ELENA_v1.mdl
Format	Simulink® File
Input Format	Simulink® Interface
Output Format	Simulink® Interface
Platform	Microsoft Windows
Execution Time	1-5 seconds
Test Platform	Processor: Intel Core Duo 2.10GHz Memory : 4GB OS: MS Windows 7 Professional
Model Developer/Keeper	Rolando Vega Díaz

3.11. VALIDATION PROCESS

Mission Profile

A comparison with the results of the mission profile was done. Its results were compared with values of the International Standard Atmosphere. The next figure shows the values of temperature and pressure for the mission profile module in ELENA. The altitude is analysed for a range between 0 and 11000 meters above the mean sea level. According with the results; as the altitude increases, ELENA derives a temperature ranging from 15 °C to -56.49 °C and a pressure ranging from 110325 Pa to 22632.63 Pa. Hence, the mission profile calculations are accepted.

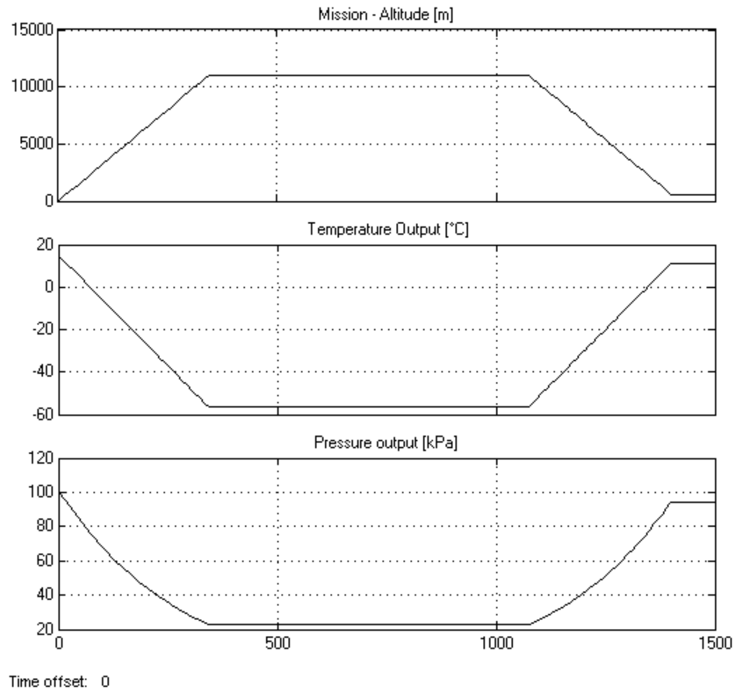


Figure 78: Mission profile validation

ECS power consumption

For the validation of the ECS pneumatic power consumption, the Airbus A321-200 has been taken as its ECS pneumatic power consumption value could be found in the literature review [2]. The A321-200 consumes around 1.2 up to 2 kg/s for both engines. The results from ELENA derive a pneumatic consumption of 1.83kg/s. Hence this calculation is acceptable.

Electric ECS power Consumption

For validation of the electric ECS concept, figures from [20]Lebherr have been taken. As seen in the following figure, their model establishes an electric power consumption average value of 1.14 kW per passenger (considering cooling).

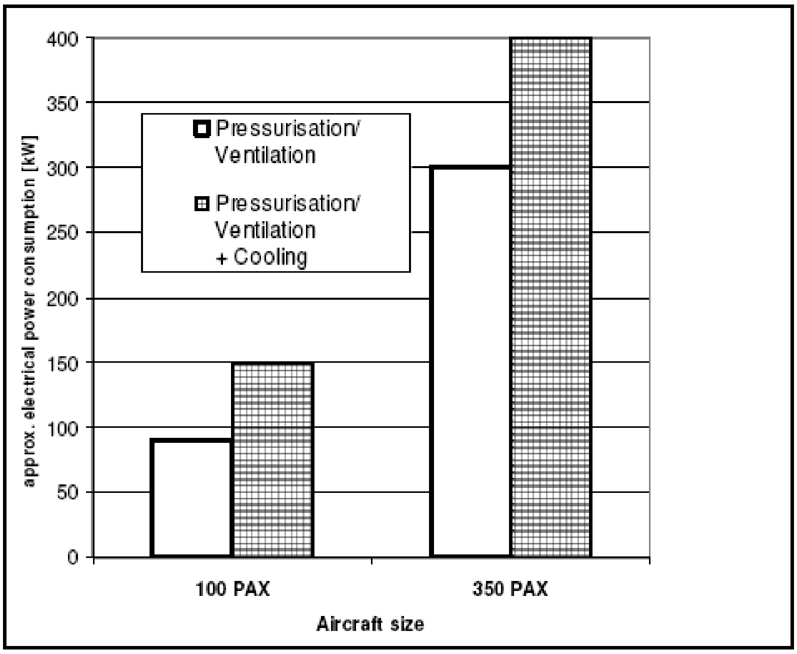


Figure 79: Electric power consumption depending on the aircraft size (image from Lebherr)

The following table has been generated with ELENA. As seen the average power consumption of the Electric ECS is 1.23 kW. Hence; comparing ELENA results with Liebherr estimations, the ELENA calculations for electric ECS power consumption are accepted.

Table 14: Electric ECS power consumption per passenger

Aircraft	Passengers	Electric power consumption	Consumption per passenger
A321-200	220	290.9 kW	1.3 kW
ATR 72-500	70	71.3 kW	1 kW
Bell 206	5	2.1 kW	0.42 kW
Average power consumption			1.23 kW

Temperature

For validation of temperature calculations, the time it takes for the conditioning pack to reach the desired cabin temperature was analysed. Hence; if the desired cabin temperature is achieved in the first 1-2 minutes, normal time for normal ECS operation, then it is possible to conclude that the calculations of thermal balance were developed with the correct procedure.

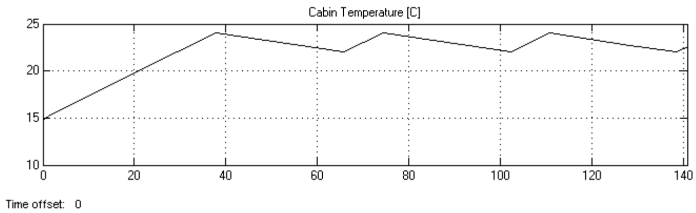


Figure 80: Cabin temperature for the A321-200

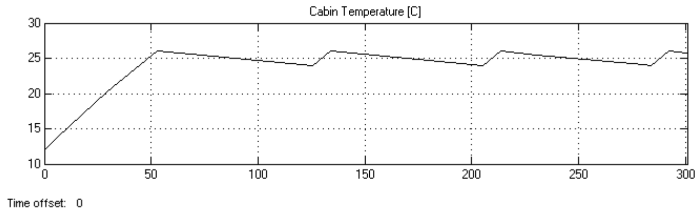


Figure 81: Cabin temperature for the ATR 72-500

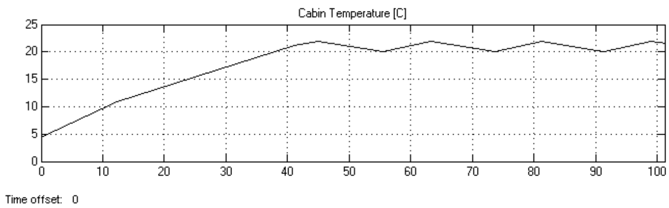


Figure 82: Cabin temperature for the Bell 206

Calculations in ELENA have shown that the average time to reach the desired temperature, for each aircraft, has ranging from 40 to 50 seconds. Furthermore, for thermostat validation; the previous figures show that once the desired temperature is achieved it is maintained by its automatic control over the manifold valves. Hence, the model has reached the temperature requirements for standard operation.

Pressure

For pressure validation the final pressures figures have been compared with standard pressurization figures. The Airbus A321-200 was used as case of study. As seen in the following figure, as the aircraft altitude increases the atmospheric pressure decreases up to 22.6 kPa. At this point the cabin must have higher pressure than the atmosphere; otherwise the passengers couldn't have a survivable cabin environment. According with structure limits, the cabin supports a maximum pressure differential of around 55 kPa. As seen on ELENA figures, as the aircraft increases its altitude up to cruise level; the cabin pressure is decrease as well but in a lower rate until it achieves 80 kPa. Hence, the model has reached an acceptable level for pressurization.

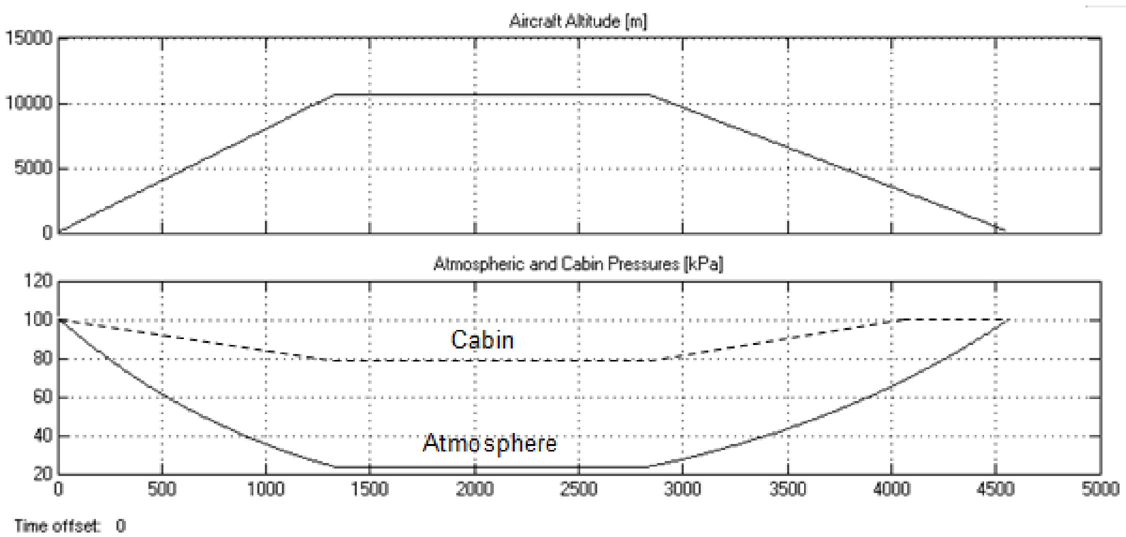


Figure 83: Pressurization validation

Fuel penalties

To perform validation of fuel penalties, the results related with ECS of a case of study from Dr Lawson [21]Lectures AVD 0504 are used. This case of study has been developed as an example to explain the procedure of this method which is described in the [11]Lectures AVD 0503. The aircraft involved in this analysis is one designed at Cranfield University to meet future needs of a military transport aircraft in Europe. This aircraft uses four turbofan engines. Further detail, considered for this validation for ELENA, is described in the following table.

Input	Data
1. All up mass	101500 kg
2. Design Fuel weight	31250 kg
3. Engine SFC at cruise	16.00 g/kNs
4. Number of engines	4
5. Isa Deviation	0 °C
6. Aircraft cruise altitude	10000 m
7. Flight Mach Number	0.7
8. Mission Range	5000 km
9. Total ECS required Mass flow	2.4 kg/s
10. ECS required Mass flow per engine	0.315 kg/s
11. Cooling mass flow ratio	0.25
12. SFC	16.99 g/kNs
13. SFC Increase due to ECS	4.746 %
14. SFC Increase due to electric ECS components	0.29443 %

The following table shows the equivalence of the data obtained with ELENA and the data of the lecture notes. As seen, all the values have an acceptable level of equivalence. The ECS fuel weight due to system weight is the value with less equivalence. This result is due to the different method applied by ELENA to calculate the system weight.

Input	AVD 0504	ELENA	Equivalence
1. ECS Fuel Flow	41.88 g/s	41.9 g/s	100 %
2. ECS Fuel Weight due to Fuel Flow	11069.34 N	11132.97 N	100.6 %

3. ECS Drag	628 N	633.54 N	100.9 %
4. ECS Fuel Weight due to Drag	2820.12 N	2859.86 N	101.4 %
5. ECS Weight	8738.3 N	8961.43 N	102.5 %
6. ECS Fuel weight due to ECS weight	2335.75 N	2632.49 N	112.7 %

To validate the penalties due to electric power the section related to the overall electric penalty has been taken. Since this part is taken only for the impact of the ECS electric power consumption; then only calculations for fuel flow and fuel weight due to fuel flow are taken into account.

Input	AVD 0504	ELENA	Equivalence
1. Electric Component Fuel Flow	2.5996 g/s	2.599 g/s	100 %
2. Electric Component Weight due to Fuel Flow	687.1 N	690.66 N	100.5 %

As seen in the previous table, the electric consumption is in acceptable levels.

CHAPTER 4 | FIXED-WING AIRCRAFT ANALISYS 1 - A CIVIL TURBO-FAN AIRPLANE

4.1. Aircraft Selection

Following the methodology to analyse the electric ECS, the first step is carried out. An Airbus 321-200 has been selected due to its current high demand on the airline transport market. Hence, the ECS of the A321-200 is simulated firstly on a conventional state to analyse its impact on the fuel penalty and other negative performance contributions in terms of system mass, drag contribution and quantity of fuel burned on an established mission profile.

The next step on the Aircraft selection is to write the required data that the model will use to perform the calculations

Aircraft Inputs:

Table 15: Aircraft inputs: Airbus A321-200

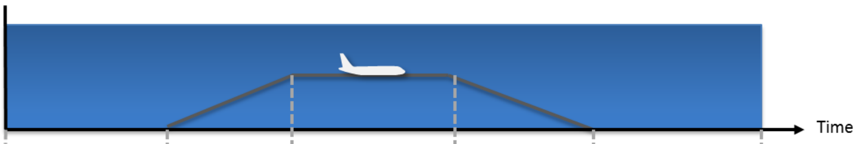
Input	Data
1. Aircraft selection code	1
2. Number of passengers	220
3. All up mass	93500 kg
4. Design fuel mass	18604 kg
5. Cabin pressurized volume	418 m^3
6. Fuselage area (Estimated)	440 m^2
7. Engine SFC at cruise	18.47 g/kNs
8. Maximum Pressurization Deferential	55 kPa
9. Engine net thrust at cruise level	32790 N
10. Number of Engines	2

4.2. Mission Profile

For this analysis, the route between London Heathrow and Paris Charles De Gaulle has been selected. According to 2008 data from the Eurostat, with 1,491,801 passengers, this air route is the third most busy for London Heathrow among European flights; and is in the 17th place among all the European airports for European air routes.

Figure 84: Mission profile: Route London Heathrow-Paris Charles De Gaulle

The following figure describes the input data for the mission profile.



Parameter	Departure Airport Altitude	Rate of Climb	Cruise	Rate of Descent	Arrival Airport Altitude
Altitude	25 m	8 m/s	10668 m	-6.1 m/s	119 m
ISA Deviation	+2 °C				
Mission Cruise Range			350 km		
Cruise Flight Mach			0.78		
Solar Isolation Index	0.5				
Wanted cabin temperature	22 °C				

Figure 85: Input data for the mission profile between the airports, London Heathrow and Paris Charles De Gaulle

The following table gives a reference for the selected data

Table 16: Mission Inputs

Mission Input	Data	Note
1. Cabin - Wanted temperature	22 °C	The range of temperatures for operation are between 18 °C and 28 °C
2. Sun isolation index	1	This value represents a sunny day without clouds. This is the maximum index value and means 250 W/m^2
3. Isa Deviation	+2 °C	For a temperature of 17 °C at the sea level
4. Aircraft cruise altitude	10668 m	Cruise altitude for the A321 following the route London-Paris where the rule RVSM establishes odd flight levels. This value is equivalent to FL350.
5. Flight Mach Number	0.78	Cruise Mach number for the A321-200
6. Mission Range	350 km	Between London Heathrow and Paris Charles de Gaulle
7. Departure airport altitude	260 m	London Heathrow
8. Destination airport altitude	270 m	Paris Charles de Gaulle
9. Rate of Climb	8 m/s	Average rate of climb
10. Rate of Descent	6.1 m/s	Average rate of descent

4.3. Conventional ECS Analysis

Pneumatic energy required

Now the pneumatic energy is calculated. This parameter will be used, as an input, over an engine performance simulation tool. The main purpose of getting this data is to compare the SFC engine with and without the extraction of this form of energy. The following table shows the results.

Table 17: Pneumatic power required

Parameter	Result
1. Total ECS required Mass flow	1.83 kg/s
2. ECS required Mass flow per engine	0.915 kg/s

Engine SFC impact

Once the simulation has been carried out, the SFC results are compared. The following table shows the achieved results.

Table 18: Engine SFC Impact

Parameter	Result
1. SFC without ECS	18.52 g/kNs
2. SFC with conventional ECS	19.23 g/kNs
3. SFC Increase	3.83%

Table 19: ECS configuration inputs

Parameter	Result
1. ECS selection code	1
2. Cooling mass flow ratio	1
3. SFC increase rate	0.0383

Conventional model impact

The next step involves the use of the SFC increasing rates on ELENA v1. The next table shows the results for the conventional model.

Mission cruise time: 25.03 min

Table 20: Conventional ECS fuel penalties

Input	Impact value	
1. ECS fuel flow due to Power-off Take	46.39	g/s
2. ECS Drag due to ram air	854.57	N
3. ECS Weight	8255	N
4. Fuel Weight due to ECS Power-off Take	687.92	N
5. Fuel Weight due to ECS Drag	234.1	N
6. Fuel Weight due to ECS Weight	175.66	N
7. Total ECS Fuel Weight	1097.6	N
8. Total ECS Weight (ECS weight + ECS fuel weight)	9352.6	N

4.4. Electric ECS Analysis

Conditioning pack configuration

The next step takes us to select the input data for the Electric-ECS. This selection is made to achieve the cabin requirements for temperature and pressure.

Table 21: ECS configuration inputs

Input	Units
1. ECS selection code	2
2. Compressor Pressure Ratio	5
3. Fan Pressure Ratio	1.3
4. Cooling mass flow ratio	1
5. Power/Weight ratio for an electric motor	4.8 kW/kg

As seen on the following figure, the input data for the compressor and fan pressure ratios and cooling mass flow was modified towards achieve desired output values of temperature and pressure. The first chart on the figure shows that the configured conditioned pack, for the Electric ECS, can deliver temperature ranges between 7 °C and 90 °C. This means that our system operates on an acceptable range of temperatures for the mixing unit “manifold”; hence, will be capable of maintain a range of temperatures between 18 °C and 30 °C for the cabin, depending on crew interest. On the other hand, the chart for delivered pressure shows that the conditioning pack can deliver a range between 90 kPa and 370 kPa. Those values are acceptable since the conditioning pack must deliver a bigger pressure than the outside one; otherwise the conditioning pack won’t be capable to pressurise the cabin.

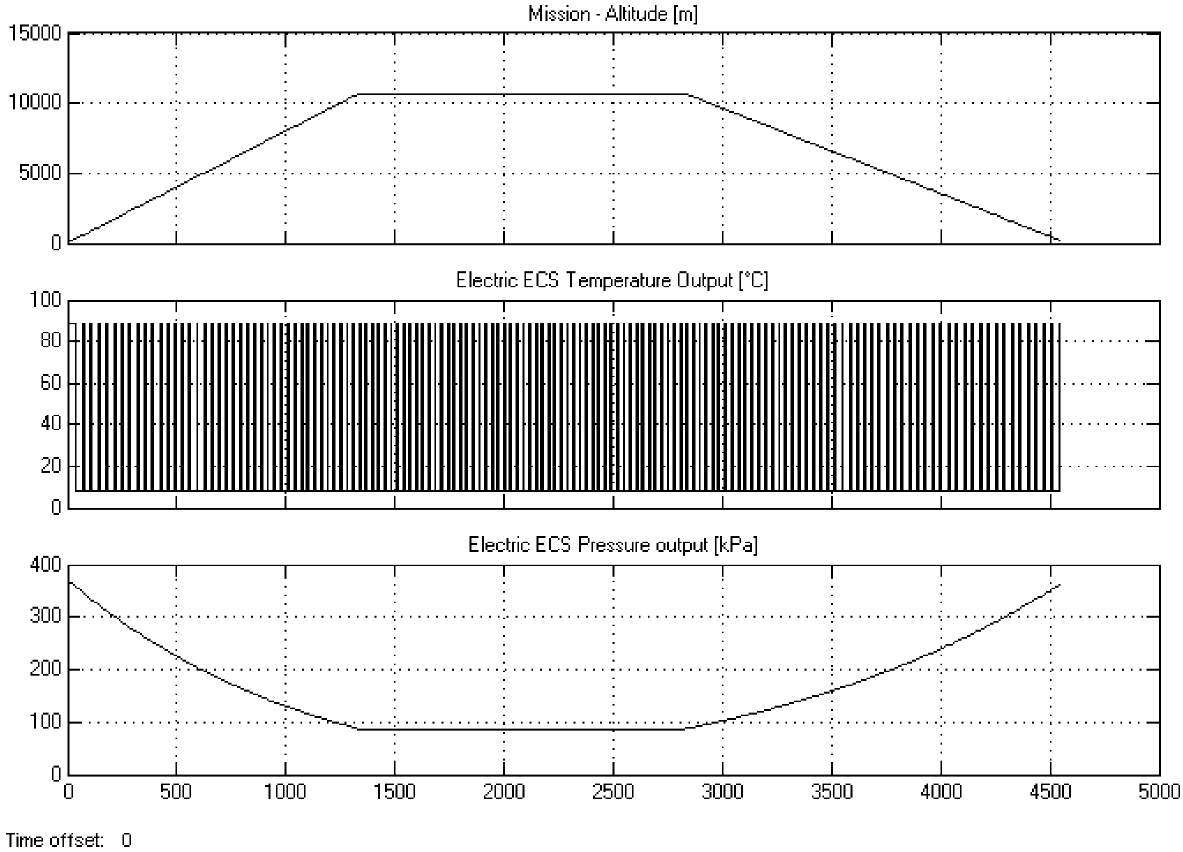


Figure 86: Time [s] vs. Altitude, Temperature and Pressure outputs delivered by the conditioning pack

As seen on the last figure. The configuration for the Electric ECS achieves the requirements of pressure and temperature at the same time. Now, the next step can be followed to analyse the cabin simulation through the proposed mission profile.

Following the framework procedure, the cabin temperature is analysed. As seen on the following figure the cabin temperature achieves its desired range. Such range is generated by controlled mixture of flows produced on the manifold. Such mixture is with the operation of valves. A range between 22 °C and 24 °C is appreciated; this range can be smoothed with action of a more automatized thermostat and a control unit.

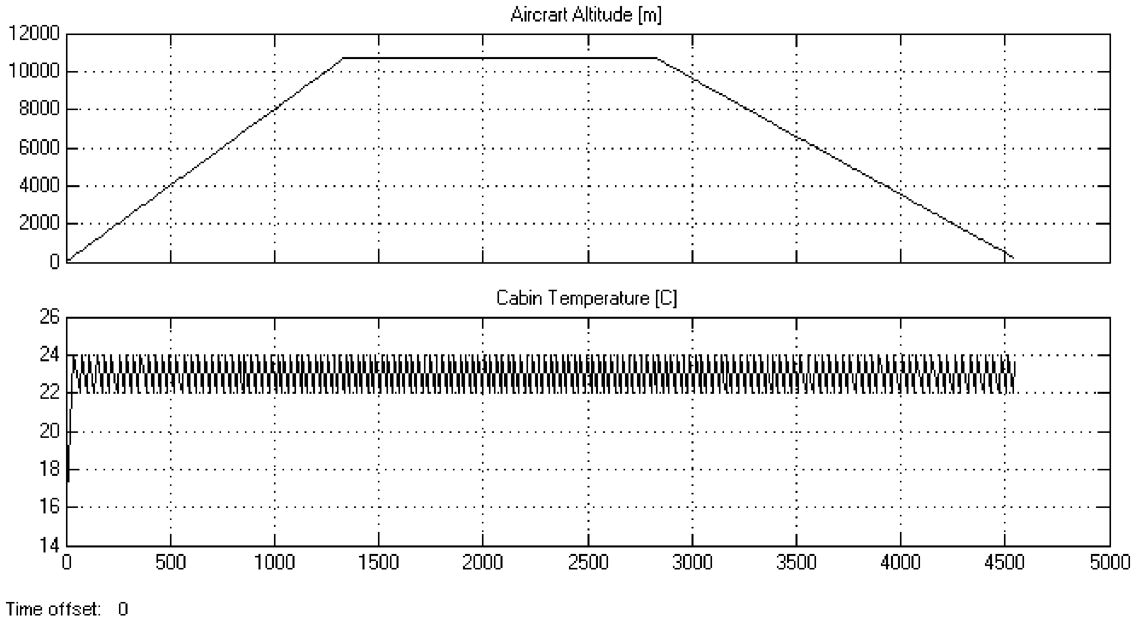


Figure 87: Time [s] vs. Altitude and Cabin Temperature

Other important factor of a conditioning pack is the capability to perform a thermal balance on a reasonable time. As seen on the following figure, the initial cabin temperature was equivalent to 15 °C. The system took about 40 seconds to warm up the cabin towards the desired temperature of 22 °C. A discrepancy of 2 °C is generated according with the thermostat capabilities.

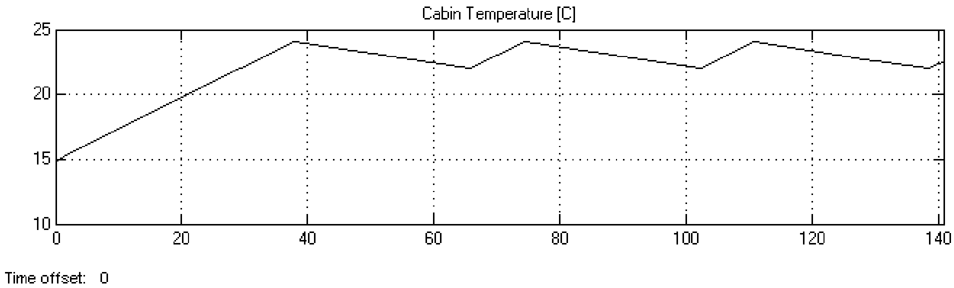


Figure 88: Time [s] vs. Cabin Temperature

The following step show the pressurization simulation been carried out. As seen on the second chart of the next figure, the conditioning pack has been capable to pressurize and depressurize the cabin during the climb and descent stages. The pressure differential has been preserved on the required range of 55 kPa as seen on the third chart. Finally in the last chart is seen how the outflow release valve has been operating to maintain the correct pressurization for the cabin.

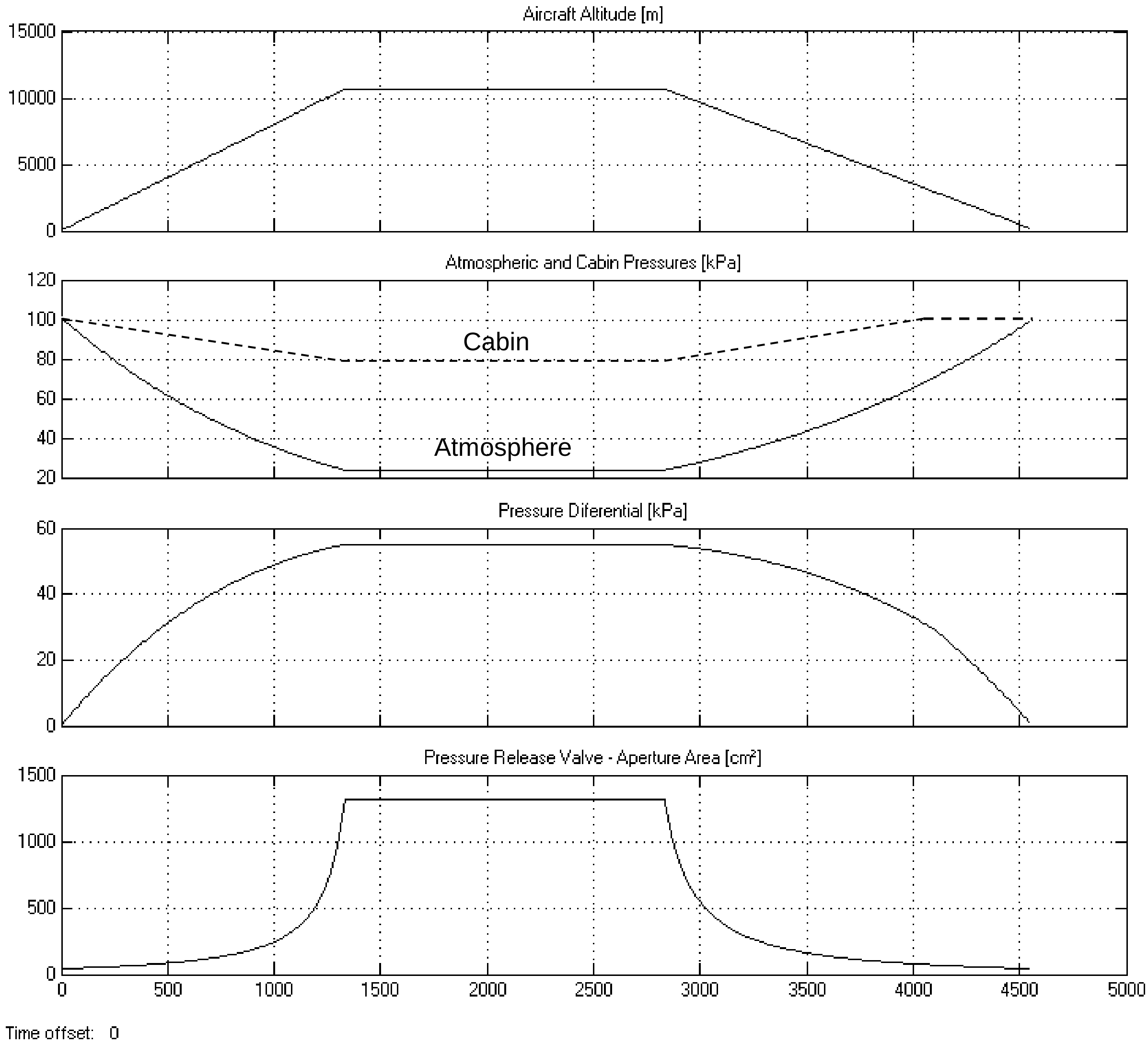


Figure 89: Time [s] vs. Altitude, Cabin and Atmospheric Pressures, Pressure Differential and Pressure Release Valve Area

The previous analysis has shown that the selected configuration for the conditioning pack achieves the air conditioning requirements.

Electric ECS electric energy required

Now the electric energy is calculated. This parameter will be used, as an input, over an engine performance simulation tool. The main purpose of getting this data is to compare the SFC engine with and without the extraction of this form of energy. The following table shows the results.

Table 22: Electric energy requirement

Parameter	Result
1. Electric ECS required electric power	290927 W
3. Electric ECS required electric power per engine	145463 W

Engine SFC impact

Once the simulation has been carried out, the SFC results are compared. The following table shows the achieved results.

Table 23: Engine SFC Impact

Parameter	Result
1. SFC w/o without ECS	18.52 g/kNs
2. SFC with conventional ECS	18.63 g/kNs
3. SFC Increase per engine	0.61%

Table 24: ECS configuration inputs

Parameter	Result
1. SFC increase rate	0.0061

Electric ECS model impact

The next step involves the use of the SFC increasing rates on ELENA v1. The next table shows the results for the conventional model.

Mission cruise time: 25.03 min

Table 25: Electric ECS fuel penalties

Input	Impact value	
1. ECS fuel flow due to Power-off Take	7.389	g/s
2. ECS Drag due to ram air	854.57	N
3. ECS Weight	9460	N
4. Fuel Weight due to ECS Power-off Take	109.56	N
5. Fuel Weight due to ECS Drag	234.1	N
6. Fuel Weight due to ECS Weight	201.27	N
7. Total ECS Fuel Weight	544.88	N
8. Total ECS Weight (ECS weight + ECS fuel weight)	10004.88	N

4.5. Results comparison

Table 26: Results comparison for the conventional and electric ECS's

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	46.39	g/s	7.389	g/s	-84.07	%
2. ECS Drag due to ram air	854.57	N	854.57	N	0.00	%
3. ECS Weight	8255	N	9460	N	14.60	%
4. Fuel Weight due to ECS Power-off Take	687.92	N	109.56	N	-84.07	%
5. Fuel Weight due to ECS Drag	234.1	N	234.1	N	0.00	%
6. Fuel Weight due to ECS Weight	175.66	N	201.27	N	14.58	%
7. Total ECS Fuel Weight	1097.6	N	544.88	N	-50.36	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	9352.6	N	10004.88	N	6.97	%

As seen on this final stage of the analysis, the electric ECS has shown a negative contribution for the aircraft performance; this is related with an increase in the total system weight in a 6.97 % over the conventional ECS. In spite of this negative result a positive and more significant result was achieved, the total mission fuel weight has been reduced in 50.36 %. This result has shown a significant reduction on the fuel required to operate the Electric ECS; consecutively in the costs and the environment al impact.

Uncertainty Analysis

Since the weight estimation used in this analysis has include a new concept due to the extra electric ECS components; then, a further analysis has been done to find the spread and the uncertainty value over the total system weight estimation. Therefore, two additional cases have been carried out; one case considers the ECS weight as 110% over its original value, and the other case considers it as 90%. The following tables show those results.

Table 27: Results comparison for the conventional and electric ECS's (with the 90 % of the original ECS weight)

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	46.39	g/s	7.389	g/s	-84.07	%
2. ECS Drag due to ram air	854.57	N	854.57	N	0.00	%
3. ECS Weight	7430	N	8514	N	14.59	%
4. Fuel Weight due to ECS Power-off Take	687.92	N	109.56	N	-84.07	%
5. Fuel Weight due to ECS Drag	234.1	N	234.1	N	0.00	%
6. Fuel Weight due to ECS Weight	158.07	N	181.14	N	14.59	%
7. Total ECS Fuel Weight	1080.04	N	524.76	N	-51.41	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	8510.04	N	9038.76	N	6.21	%

Table 28: Results comparison for the conventional and electric ECS's (with the 110 % of the original ECS weight)

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	46.39	g/s	7.389	g/s	-84.07	%
2. ECS Drag due to ram air	854.57	N	854.57	N	0.00	%
3. ECS Weight	9081	N	10406.19	N	14.59	%
4. Fuel Weight due to ECS Power-off Take	687.92	N	109.56	N	-84.07	%
5. Fuel Weight due to ECS Drag	234.1	N	234.1	N	0.00	%
6. Fuel Weight due to ECS Weight	193.19	N	221.39	N	14.60	%
7. Total ECS Fuel Weight	1115.16	N	565.01	N	-49.33	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	10196.16	N	10971.2	N	7.60	%

The following table shows that for the conventional ECS the spread is of 1686 N, which represents an uncertainty value of 18 %. In the case of the electric ECS the spread is of 1932 N, which represents an uncertainty value of 19.3 %.

Total ECS Weight (ECS weight + ECS fuel weight)	100%	90%		110%		Spread [N]	Uncertainty [%]
	Value [N]	Value [N]	Difference [%]	Value [N]	Difference [%]		
Conventional ECS	9353	8510	-9.0	10196	9.0	1686	18.0
Electric ECS	10005	9039	-9.7	10971	9.7	1932	19.3

4.6. Fuel Cost

Taking the results from ELENA and applying the methodology of Prof Dieter Scholz, mentioned in the chapter 2. The following chart has been generated. The number of flights are ranging from 2200 to 3800, which are values considered from 7 to 12 daily flights for the selected mission in the study. The number of days taken from the 365 days in the year is estimated as 320; such estimation was done considered the days which the aircraft is in-operative due maintenance and flight cancellations. Further analysis can be done in future research to estimate more accurately this value.

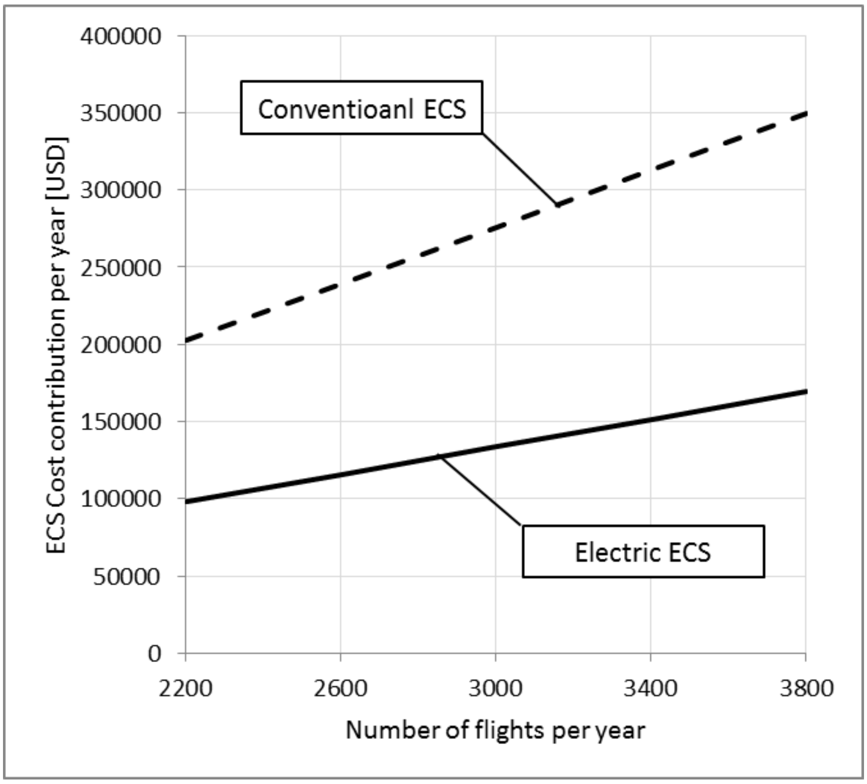


Figure 90: Estimated fuel cost for the electric and conventional ECS's in the Airbus A321-200

CHAPTER 5 | FIXED-WING AIRCRAFT ANALISYS 2 - A REGIONAL TURBO-PROP AIRPLANE

5.1. Aircraft Selection

Following the methodology to analyse the electric ECS, the first step is carried out. Differently form the last case of study; an ATR 72-500 is selected towards compare the ECS energy impact for a regional turbo-prop airplane. Hence, the ECS of the ATR 72-500 is simulated firstly on a conventional state to analyse its impact on the fuel penalty and other negative performance contributions in terms of system mass, drag contribution and quantity of fuel burned on an established mission profile.

The next step on the Aircraft selection is to write the required data that the model will use to perform the calculations.

Aircraft Inputs [16]**:**

Table 29: Aircraft inputs: ATR 72-500

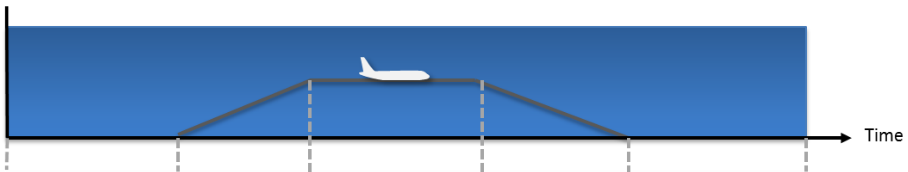
Input	Data
1. Aircraft selection code	1
2. Number of passengers	76
3. All up mass	22500 kg
4. Design Fuel weight	5000 kg
5. Cabin pressurized volume (Estimated)	112 m^3
6. Fuselage Area (Estimated)	131 m^2
7. Engine SFC at cruise	0.2231 kg/Wh
8. Maximum Pressurization Deferential	55 kPa
9. Engine net power at cruise level	1200260 W
10. Number of engines	2

5.2. Mission Profile

For this analysis, the route between Barcelona El Prat and Madrid Barajas has been selected. According to 2008 data from the Eurostat, with 3,497,696 passengers, this air route is the first most busy among European passenger air routes.

Figure 91: Mission profile: Route Barcelona El Prat and Madrid Barajas

The following figure describes the input data for the mission profile.



Parameter	Departure Airport Altitude	Rate of Climb	Cruise	Rate of Descent	Arrival Airport Altitude
Altitude	4 m	8 m/s	7315.2 m	-6.1 m/s	610 m
ISA Deviation			-3 °C		
Mission Cruise Range			508 km		
Cruise Flight Mach			0.46		
Solar Isolation Index			0.8		
Wanted cabin temperature			24 °C		

Figure 92: Input data for the mission profile between Barcelona El Prat and Madrid Barajas

The following table gives a reference for the selected data

Mission Input	Data	Note
1. Cabin - Wanted temperature	24 °C	The range of temperatures for operation are between 18 °C and 28 °C
2. Sun Heating Index	0.8	This index represents a sunny day with a little few clouds.
3. Isa Deviation	-3 °C	For a temperature of 12 °C at the sea level
4. Aircraft cruise altitude	7315.2 m	Cruise altitude for the ATR 72 following the route London-Paris where the rule RVSM establishes even flight levels. This value is equivalent to FL240.
5. Flight Mach Number	0.46	Cruise Mach number for the ATR 72-500
6. Mission Range	508 km	Between Barcelona El Prat and Madrid Barajas
7. Departure airport altitude	4 m	Barcelona El Prat
8. Destination airport altitude	610 m	Madrid Barajas
9. Rate of Climb	8 m/s	Average rate of climb
10. Rate of Descent	-6.1 m/s	Average rate of descent

5.3. Conventional ECS Analysis

Pneumatic energy required

Now the pneumatic energy is calculated. This parameter will be used, as an input, over an engine performance simulation tool. The main purpose of getting this data is to compare the SFC engine with and without the extraction of this form of energy. The following table shows the results.

Table 30: Pneumatic power required

Parameter	Result
1. Total ECS required Mass flow	0.63 kg/s
2. ECS required Mass flow per engine	0.315 kg/s

Engine SFC impact

Once the simulation has been carried out, the SFC results are compared. The following table shows the achieved results.

Table 31: Engine SFC Impact

Parameter	Result
1. SFC w/o without ECS	0.223 kg/kWh
2. SFC with conventional ECS	0.253 kg/kWh
3. SFC Increase	13.33%

Table 32: ECS configuration inputs

Parameter	Result
1. ECS selection code	1
2. Cooling mass flow ratio	0.7
3. SFC increase rate	0.1333

Conventional model impact

The next step involves the use of the SFC increasing rates on ELENA v1. The next table shows the results for the conventional model.

Mission cruise time: 59.36 min

Table 33: Conventional ECS fuel penalties

Input	Impact value	
1. ECS fuel flow due to Power-off Take	71.39	g/s
2. ECS Drag due to ram air	152.96	N
3. ECS Weight	1987	N
4. Fuel Weight due to ECS Power-off Take	2613.98	N
5. Fuel Weight due to ECS Drag	1.249	N
6. Fuel Weight due to ECS Weight	193.71	N
7. Total ECS Fuel Weight	2808.93	N
8. Total ECS Weight (ECS weight + ECS fuel weight)	4795.93	N

5.4. Electric ECS Analysis

Conditioning pack configuration

The next step takes us to select the input data for the Electric-ECS. This selection is made to achieve the cabin requirements for temperature and pressure.

Table 34: ECS configuration inputs

Input	Units
1. ECS selection code	2
2. Compressor Pressure Ratio	3.1
3. Fan Pressure Ratio	1.3
4. Cooling mass flow ratio	0.7
5. Power/Weight ratio for an electric motor	4.8 kW/kg

As seen on the next figure, the input data for the compressor and fan pressure ratios and cooling mass flow was modified towards achieve desired output values of temperature and pressure. The first chart on the figure shows that the configured conditioned pack, for the Electric ECS, can deliver temperature ranges between 10 °C and 65 °C. This means that our system operates on an acceptable range of temperatures for the mixing unit “manifold”; hence, will be capable of maintain a range of temperatures between 18 °C and 30 °C for the cabin, depending on crew interest. On the other hand, the chart for delivered pressure shows that the conditioning pack can deliver a range between 95 kPa and 250 kPa. Those values are acceptable since the conditioning pack must deliver a bigger pressure than the outside one; otherwise the conditioning pack won’t be capable to pressurise the cabin.

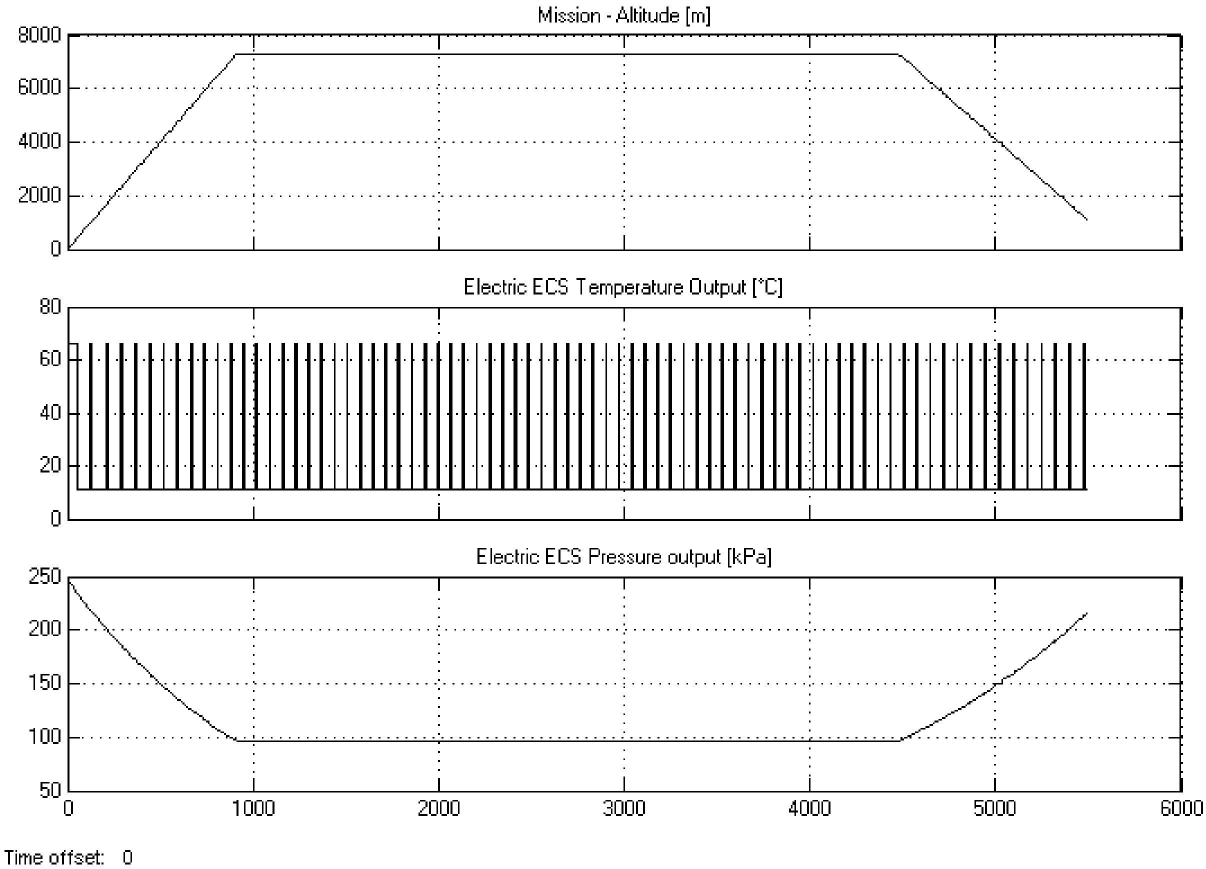


Figure 93: Time [s] vs. Altitude, Temperature and Pressure outputs delivered by the conditioning pack

As seen on the last figure. The configuration for the Electric ECS achieves the requirements of pressure and temperature at the same time. Now, the next step can be followed to analyse the cabin simulation through the proposed mission profile.

Following the framework procedure, the cabin temperature is analysed. As seen on the following figure the cabin temperature achieves its desired range. Such range is generated by controlled mixture of flows produced on the manifold. Such mixture is with the operation of valves. A range 25 °C is appreciated; this range can be smoothed with action of a more automatized thermostat and a control unit.

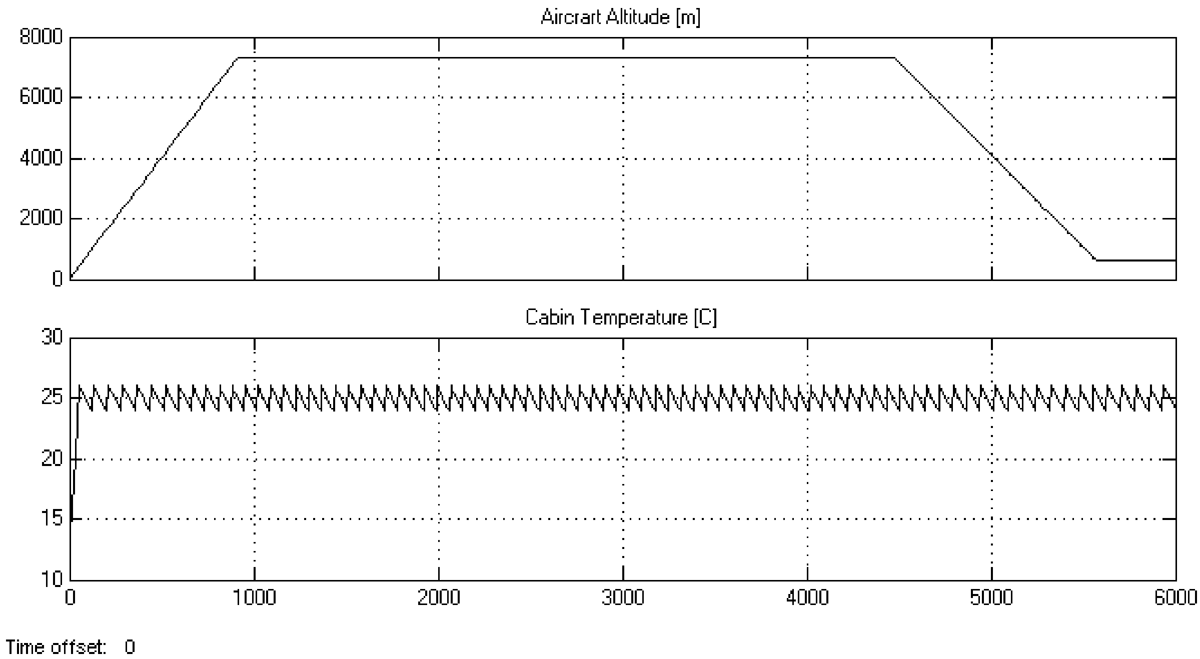


Figure 94: Time [s] vs. Altitude and Cabin Temperature

Other important factor of a conditioning pack is the capability to perform a thermal balance on a reasonable time. As seen on the following figure, the initial cabin temperature was equivalent to 15 °C. The system took about 50 seconds to warm up the cabin towards the desired temperature of 24 °C. A discrepancy of 2 °C is generated according with the thermostat capabilities.

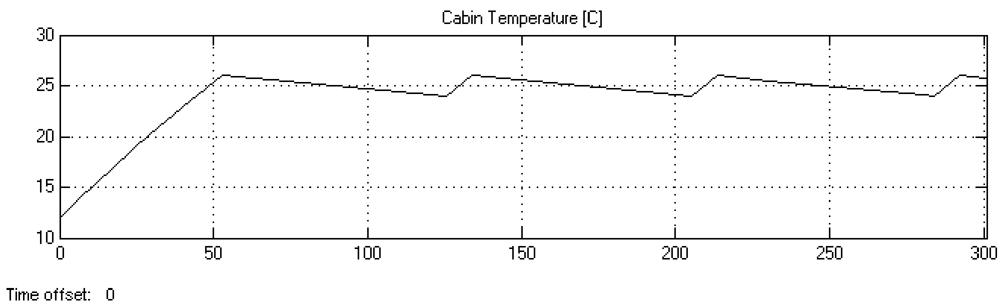


Figure 95: Time [s] vs. Cabin Temperature

The following step show the pressurization simulation been carried out. As seen on the second chart of the next figure, the conditioning pack has been capable to pressurize and depressurize the cabin during the climb and descent stages. The pressure differential has been preserved on the required range of 55 kPa as seen on the third chart. Finally in the last chart is seen how the outflow release valve has been operating to maintain the correct pressurization for the cabin.

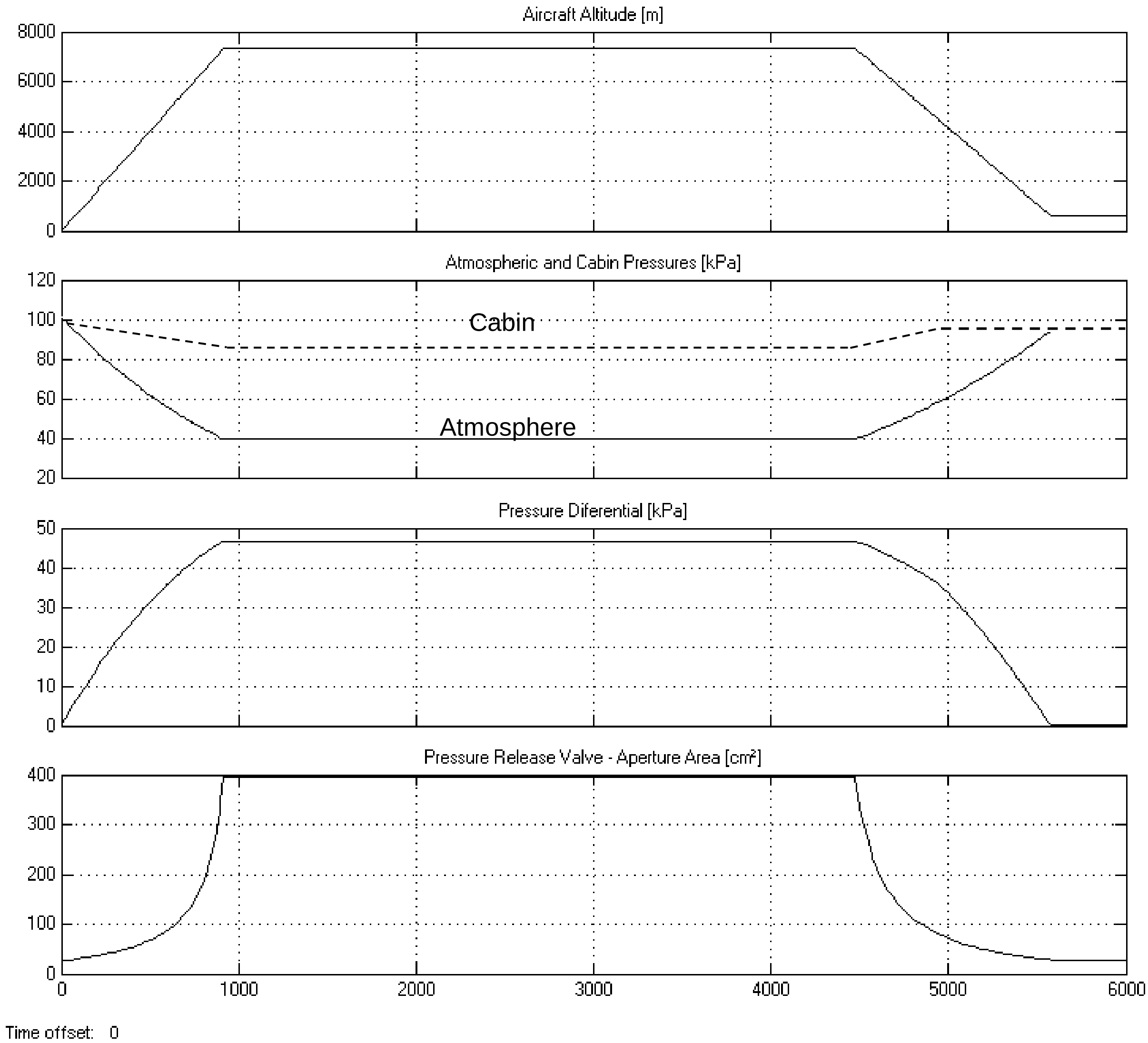


Figure 96: Time [s] vs. Altitude, Cabin and Atmospheric Pressures, Pressure Differential and Pressure Release Valve Area

The previous analysis has shown that the selected configuration for the conditioning pack achieves the air conditioning requirements.

Electric ECS electric energy required

Table 35: Electric energy required

Parameter	Result
1. Electric ECS required electric power	71307.4 W
2. Electric ECS required electric power per engine	35653.7 W

Engine SFC impact

Table 36: Engine SFC Impact

Parameter	Result
1. SFC w/o without ECS	0.2235 kg/kWh
2. SFC with conventional ECS	0.2306 kg/kWh
3. SFC Increase	3.18%

Table 37: ECS configuration inputs

Parameter	Result
1. SFC increase rate	0.0318

Electric ECS model impact

Mission cruise time: 59.36 min

Table 38: Electric ECS fuel penalties

Input	Impact value	
1. ECS fuel flow due to Power-off Take	17.03	g/s
2. ECS Drag due to ram air	152.96	N
3. ECS Weight	2280	N
4. Fuel Weight due to ECS Power-off Take	623.59	N
5. Fuel Weight due to ECS Drag	1.249	N
6. Fuel Weight due to ECS Weight	222.31	N
7. Total ECS Fuel Weight	847.15	N
8. Total ECS Weight (ECS weight + ECS fuel weight)	3127.15	N

5.5. Results comparison

Table 39: Results comparison for the conventional and electric ECS's

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	71.39	g/s	17.03	g/s	-76.15	%
2. ECS Drag due to ram air	152.96	N	152.96	N	0.00	%
3. ECS Weight	1987	N	2280	N	14.75	%
4. Fuel Weight due to ECS Power-off Take	2613.98	N	623.59	N	-76.14	%
5. Fuel Weight due to ECS Drag	1.249	N	1.249	N	0.00	%
6. Fuel Weight due to ECS Weight	193.71	N	222.31	N	14.76	%
7. Total ECS Fuel Weight	2808.93	N	847.15	N	-69.84	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	4795.93	N	3127.15	N	-34.80	%

As seen on this final stage of the analysis, the electric ECS has shown a positive contribution for the aircraft performance; this is related with a decrease in the total system weight in a 34.80 % over the conventional ECS. Additionally, a further positive and more significant result was achieved; the total mission fuel weight has been reduced in 69.84 %. This result has shown a significant reduction on the fuel required to operate the Electric ECS; consecutively in the costs and the environment al impact.

Uncertainty Analysis

Since the weight estimation used in this analysis has include a new concept due to the extra electric ECS components; then, a further analysis has been done to find the spread and the uncertainty value over the total system weight estimation. Therefore, two additional cases have been carried out; one case considers the ECS weight as 110% over its original value, and the other case considers it as 90%. The following tables show those results.

Table 40: Results comparison for the conventional and electric ECS's (with the 90 % of the original ECS weight)

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	71.39	g/s	17.03	g/s	-76.15	%
2. ECS Drag due to ram air	152.96	N	152.96	N	0.00	%
3. ECS Weight	1788	N	2052	N	14.77	%
4. Fuel Weight due to ECS Power-off Take	2613.98	N	623.59	N	-76.14	%
5. Fuel Weight due to ECS Drag	1.249	N	1.249	N	0.00	%
6. Fuel Weight due to ECS Weight	174.34	N	200.08	N	14.76	%
7. Total ECS Fuel Weight	2789.56	N	824.92	N	-70.43	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	4577.56	N	2876.92	N	-37.15	%

Table 41: Results comparison for the conventional and electric ECS's (with the 110 % of the original ECS weight)

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	71.39	g/s	17.03	g/s	-76.15	%
2. ECS Drag due to ram air	152.96	N	152.96	N	0.00	%
3. ECS Weight	2185	N	2508	N	14.78	%
4. Fuel Weight due to ECS Power-off Take	2613.98	N	623.59	N	-76.14	%
5. Fuel Weight due to ECS Drag	1.249	N	1.249	N	0.00	%
6. Fuel Weight due to ECS Weight	213.08	N	244.54	N	14.76	%
7. Total ECS Fuel Weight	2828.3	N	869.38	N	-69.26	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	5013.3	N	3377.38	N	-32.63	%

The following table shows that for the conventional ECS the spread is of 436 N, which represents an uncertainty value of 9.1 %. In the case of the electric ECS the spread is of 500 N, which represents an uncertainty value of 16.0 %.

Total ECS Weight (ECS weight + ECS fuel weight)	100%	90%		110%		Spread [N]	Uncertainty [%]
	Value [N]	Value [N]	Difference [%]	Value [N]	Difference [%]		
Conventional ECS	4796	4578	-4.6	5013	4.5	436	9.1
Electric ECS	3127	2877	-8.0	3377	8.0	500	16.0

5.6. Fuel Cost

Taking the results from ELENA and applying the methodology of Prof Dieter Scholz, mentioned in the chapter 2. The following chart has been generated. The number of flights are ranging from 2200 to 3800, which are values considered from 7 to 12 daily flights for the selected mission in the study. The number of days taken from the 365 days in the year is estimated as 320; such estimation was done considered the days which the aircraft is in-operative due maintenance and flight cancellations. Further analysis can be done in future research to estimate more accurately this value.

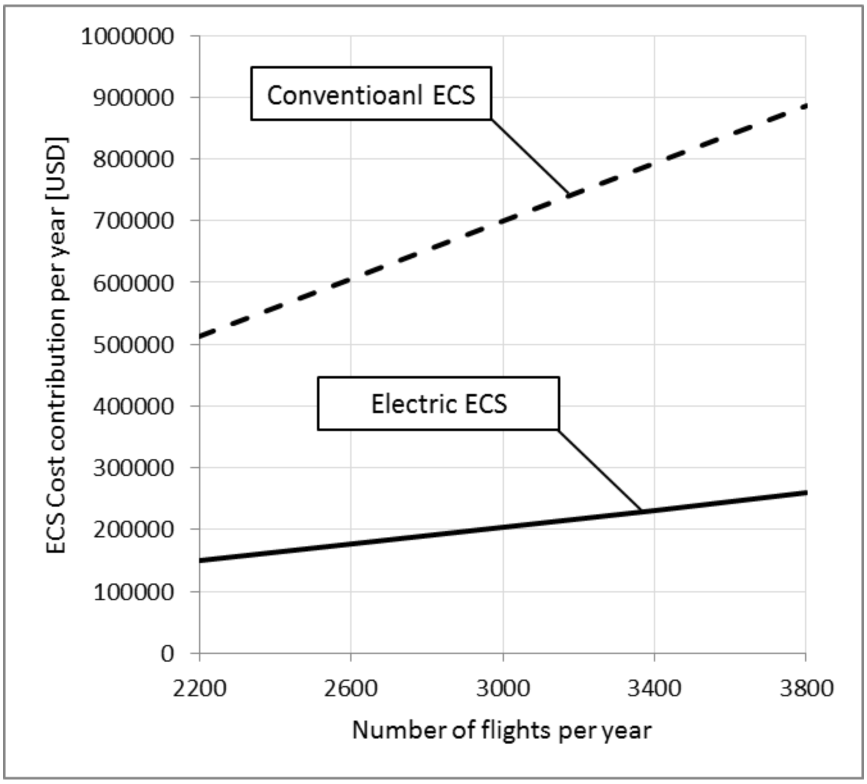


Figure 97: Estimated fuel cost for the electric and conventional ECS's in the ATR 72-500

CHAPTER 6 | ROTARY-WING AIRCRAFT ANALISYS FOR A 5 PASSENGERS HELICOPTER

6.1. Aircraft Selection

Following the methodology to analyse the electric ECS, the first step is carried out. A Bell 206 has been selected to assess the application of an electric ECS. Hence, a conventional ECS for the Bell 206 is simulated firstly on a conventional state to analyse its impact on the fuel penalty and other negative performance contributions in terms of system mass, drag contribution and quantity of fuel burned on an established mission profile.

The next step on the Aircraft selection is to write the required data that the model will use to perform the calculations

Aircraft Inputs:

Table 42: Aircraft inputs: Bell 206

Input	Units
1. Aircraft selection code	2
2. Number of passengers	5
3. All up mass	1451 kg
4. Design Fuel weight	230 kg
5. Cabin volume (Estimated)	2.2 m^3
6. Fuselage Area (Estimated)	15 m^2
7. Engine SFC at cruise	0.319 kg/Wh
8. Engine power at cruise level	295010 W
9. Number of engines	1

6.2. Mission Profile

For this analysis a local route has been selected; from Cranfield University Airport to London City Airport. This route covers 70 km and is completed on approximately 20 minutes.

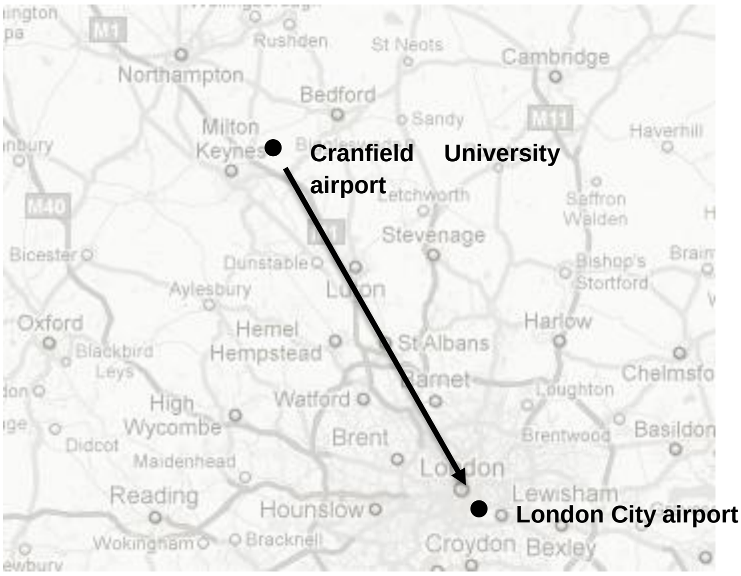
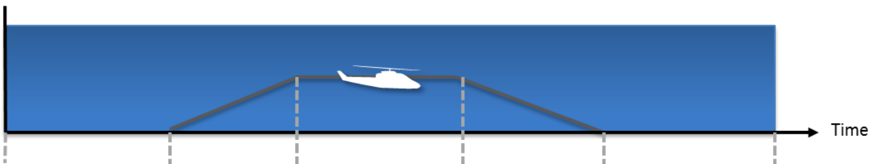


Figure 98: Mission profile: Route Cranfield University Airport to London City Airport

The following figure describes the input data for the mission profile.



Parameter	Departure Airport Altitude	Rate of Climb	Cruise	Rate of Descent	Arrival Airport Altitude
Altitude	109 m	8 m/s	3000 m	-6.1 m/s	6 m
ISA Deviation			-10 °C		
Mission Cruise Range			70 km		
Cruise Flight Mach			0.18		
Solar Isolation Index			0.3		
Wanted cabin temperature			20 °C		

Figure 99: Input data for the mission profile between Cranfield University Airport and London City Airport

The following table gives a reference for the selected data

Mission Input	Units	Note
1. Cabin - Wanted temperature	20 °C	The range of temperatures for operation are between 18 °C and 28 °C
2. Sun Heating Index	0.3	This index represents a sunny day with a little few clouds.
3. Isa Deviation	-10 °C	For a temperature of 5 °C at the sea level
4. Aircraft cruise altitude	3000 m	Typical high cruise level for a helicopter
5. Flight Mach Number	0.18	Cruise Mach number for the Bell 206
6. Mission Range	70 km	Between Cranfield University Airport and London City Airport
7. Departure airport altitude	109 m	Cranfield University Airport
8. Destination airport altitude	6 m	London City Airport
9. Rate of Climb	8 m/s	Average rate of climb
10. Rate of Descent	-6.1 m/s	Average rate of descent

6.3. Conventional ECS Analysis

Now the pneumatic energy is calculated. This parameter will be used, as an input, on an engine performance simulation tool. The main purpose of getting this data is to compare the SFC engine with and without the extraction of this form of energy.

Pneumatic energy required

Table 43: Pneumatic power required

Parameter	Result
1. Total ECS required Mass flow	0.0415 kg/s
2. ECS required Mass flow per engine	0.0415 kg/s

Engine SFC impact

Table 44: Engine SFC Impact

Parameter	Result
1. SFC w/o without ECS	0.319 kg/kWh
2. SFC with conventional ECS	0.331 kg/kWh
3. SFC Increase	3.539 %

Table 45: ECS configuration inputs

Parameter	Result
1. ECS selection code	1
2. Cooling mass flow ratio	0.7
3. SFC increase rate	0.03539

Conventional model impact

Mission cruise time: 20.08 min

Table 46: Conventional ECS fuel penalties

Input	Impact value	
1. ECS fuel flow due to Power-off Take	0.9251	g/s
2. ECS Drag due to ram air	4.1	N
3. ECS Weight	128.1	N
4. Fuel Weight due to ECS Power-off Take	11.06	N
5. Fuel Weight due to ECS Drag	0.004343	N
6. Fuel Weight due to ECS Weight	3	N
7. Total ECS Fuel Weight	14.07	N
8. Total ECS Weight (ECS weight + ECS fuel weight)	142.17	N

6.4. Electric ECS Analysis

Conditioning pack configuration

The next step takes us to select the input data for the Electric-ECS. This selection is made to achieve the cabin requirements for temperature and pressure.

Table 47: ECS configuration inputs

Input	Units
1. ECS selection code	2
2. Compressor Pressure Ratio	1.7
3. Fan Pressure Ratio	1.2
4. Cooling mass flow ratio	0.7
5. Power/Weight ratio for an electric motor	4.8 kW/kg

As seen on the next figure, the input data for the compressor and fan pressure ratios and cooling mass flow was modified towards achieve desired output values of temperature and pressure. The first chart on the figure shows that the configured conditioned pack, for the Electric ECS, can deliver temperature ranges between 7 °C and 90 °C. This means that our system operates on an acceptable range of temperatures for the mixing unit “manifold”; hence, will be capable of maintain a range of temperatures between 18 °C and 30 °C for the cabin, depending on crew interest.

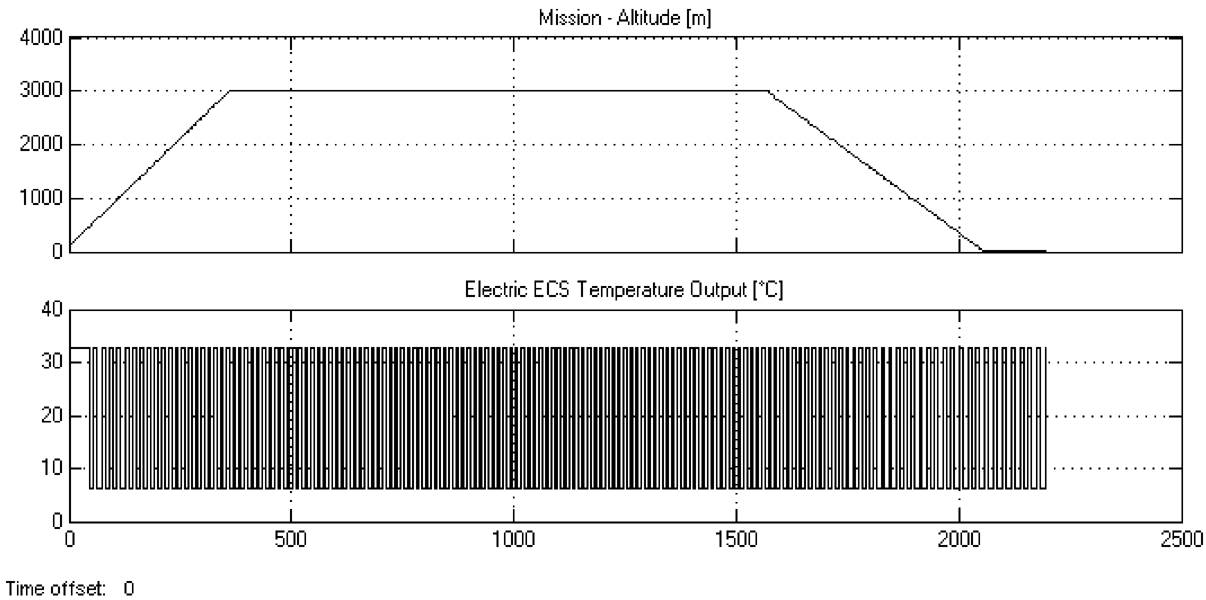


Figure 100: Temperature range output delivered by the conditioning pack

As seen on the last figure. The configuration for the Electric ECS achieves the requirements of pressure and temperature at the same time. Now, the next step can be followed to analyse the cabin simulation through the proposed mission profile.

Following the framework procedure, the cabin temperature is analysed. As seen on the following figure the cabin temperature achieves its desired range. Such range is generated by controlled mixture of flows produced on the manifold. Such mixture is with the operation of valves. A range between 20 °C and 22 °C is appreciated; this range can be smoothed with action of a more automatized thermostat and a control unit.

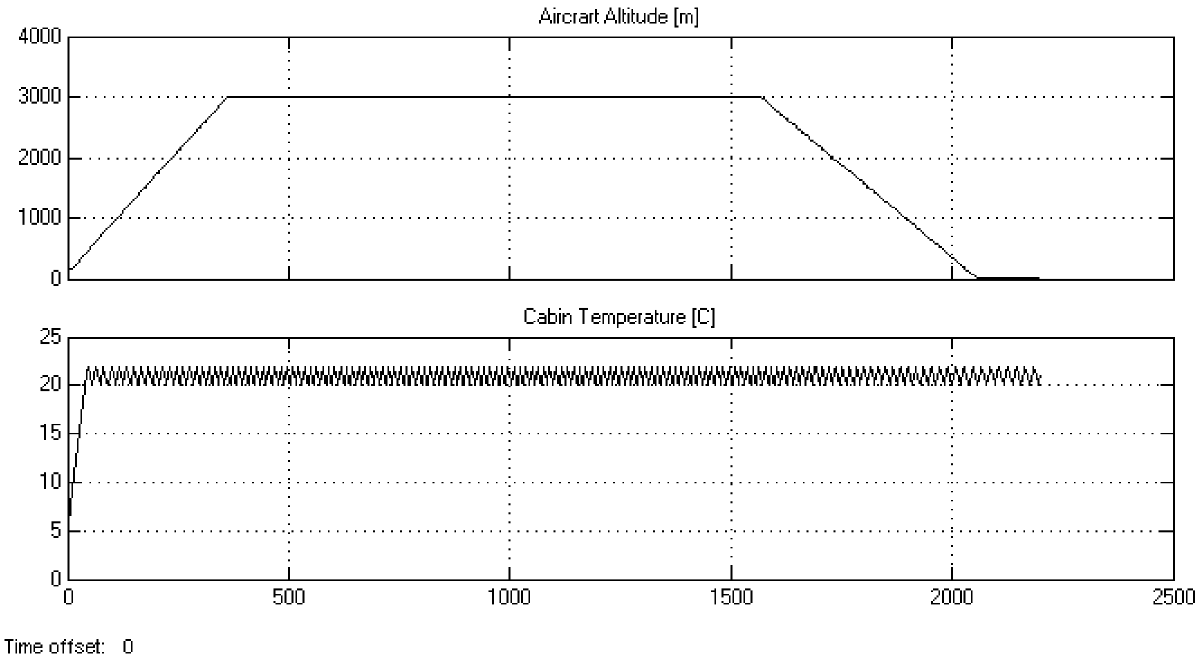


Figure 101: Temperature output delivered by the conditioning pack

Other important factor of a conditioning pack is the capability to perform a thermal balance on a reasonable time. As seen on the following figure, the initial cabin temperature was equivalent to 5 °C. The system took about 44 seconds to warm up the cabin towards the desired temperature of 20 °C. A discrepancy of 2 °C is generated according with the thermostat capabilities.

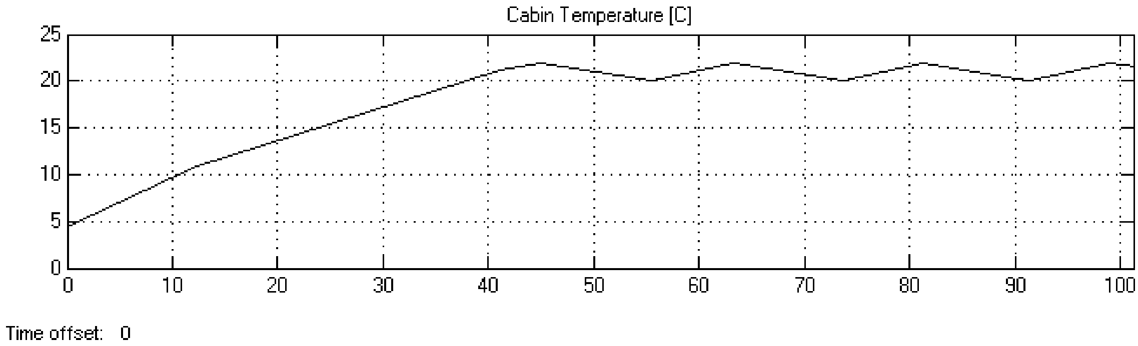


Figure 102: Temperature output delivered by the conditioning pack

Electric ECS electric energy required

Table 48: Electric ECS energy required

Parameter	Result
1. Electric ECS required electric power	2189.6 W
2. Electric ECS required electric power per engine	2189.6 W

Engine SFC impact

Table 49: Engine SFC Impact

Parameter	Result
1. SFC w/o without ECS	0.319 kg/kWh
2. SFC with conventional ECS	0.322 kg/kWh
3. SFC Increase	0.752 %

Table 50: ECS configuration inputs

Parameter	Result
1. SFC increase rate	0.00752

Electric ECS model impact

Mission cruise time: 20.08 min

Table 51: Electric ECS fuel penalties

Input	Impact value	
1. ECS fuel flow due to Power-off Take	0.1966	g/s
2. ECS Drag due to ram air	4.1	N
3. ECS Weight	137.2	N
4. Fuel Weight due to ECS Power-off Take	2.35	N
5. Fuel Weight due to ECS Drag	0.004343	N
6. Fuel Weight due to ECS Weight	3.22	N
7. Total ECS Fuel Weight	5.57	N
8. Total ECS Weight (ECS weight + ECS fuel weight)	142.77	N

6.5. Combustion heater

The Environmental Control System of a helicopter is simulated, using the previous version tool, to obtain its energy consumption; consequently the energy is analysed in terms fuel flow under certain components configuration and a fixed operational point. The simulation is carried out under low fidelity conditions for combustion heater conditioning system.

Table 52: Combustion Heater requirements

Parameter	Value	Note
Number of Passengers	5	Bell 206
CS29 Air Flow per Passenger	0.0083 kg/s	Although the CS29 establish 0.00645kg/s, some literature establishes 0.0083kg/s for design purposes.
Heat Load per Passenger	110W	This is an average taking form the heat load produced by passengers and crew members which is 70W and 650W respectively. This average is considered as the best option for a helicopter.
	10 m²	Assumed for a small helicopter
Cabin Skin Heat Conductivity	1.4 W/m²K	For a normal material.
Cabin Volume	2.26 m³	Bell 206 Estimated

Heating mission Scenario with Combustion Heater

Only a heating capability can be carried out in this scenario, thus cold ambient conditions are set.

Table 53: Combustion Heater requirements

Parameter	Value	Note
Temperature of the cabin	5°C	Assumed
Solar Radiation	0W/m^2	For a night conditions
ISA Deviation	-20°C	For winter conditions
Altitude [0m - 11000m]	3000	Performing a cruise flight

Table 54: Combustion Heater results

Parameter	Results
1. Combustion heater fuel flow	0.3327 g/s
2. Electric power	727.4 W

6.6. Results comparison

Table 55: Results comparison for the conventional and electric ECS's

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	0.9251	g/s	0.1966	g/s	-78.75	%
2. ECS Drag due to ram air	4.1	N	4.1	N	0.00	%
3. ECS Weight	128.1	N	137.2	N	7.10	%
4. Fuel Weight due to ECS Power-off Take	11.06	N	2.35	N	-78.75	%
5. Fuel Weight due to ECS Drag	0.004343	N	0.004343	N	0.00	%
6. Fuel Weight due to ECS Weight	3	N	3.22	N	7.33	%
7. Total ECS Fuel Weight	14.07	N	5.57	N	-60.41	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	142.17	N	142.77	N	0.42	%

As seen on this final stage of the analysis, the electric ECS has shown a negative contribution for the aircraft performance; this is related with an increase in the total system weight in a 0.42 % over the conventional ECS. In spite of this negative result a positive and more significant result was achieved, the total mission fuel weight has been reduced in 60.41 %. This result has shown a significant reduction on the fuel required to operate the Electric ECS; consecutively in the costs and the environment al impact.

Uncertainty Analysis

Since the weight estimation used in this analysis has include a new concept due to the extra electric ECS components; then, a further analysis has been done to find the spread and the uncertainty value over the total system weight estimation. Therefore, two additional cases have been carried out; one case considers the ECS weight as 110% over its original value, and the other case considers it as 90%. The following tables show those results.

Table 56: Results comparison for the conventional and electric ECS's (with the 90 % of the original ECS weight)

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	0.9251	g/s	0.1966	g/s	-78.75	%
2. ECS Drag due to ram air	4.1	N	4.1	N	0.00	%
3. ECS Weight	115.3	N	123.5	N	7.11	%
4. Fuel Weight due to ECS Power-off Take	11.06	N	2.35	N	-78.75	%
5. Fuel Weight due to ECS Drag	0.004343	N	0.004343	N	0.00	%
6. Fuel Weight due to ECS Weight	2.7	N	2.9	N	7.41	%
7. Total ECS Fuel Weight	13.77	N	5.25	N	-61.87	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	129.07	N	128.75	N	-0.25	%

Table 57: Results comparison for the conventional and electric ECS's (with the 110 % of the original ECS weight)

Input	Conventional ECS		Electric ECS		Difference Electric to Conventional	
1. ECS fuel flow due to Power-off Take	0.9251	g/s	0.1966	g/s	-78.75	%
2. ECS Drag due to ram air	4.1	N	4.1	N	0.00	%
3. ECS Weight	140.9	N	151	N	7.17	%
4. Fuel Weight due to ECS Power-off Take	11.06	N	2.35	N	-78.75	%
5. Fuel Weight due to ECS Drag	0.004343	N	0.004343	N	0.00	%
6. Fuel Weight due to ECS Weight	3.3	N	3.54	N	7.27	%
7. Total ECS Fuel Weight	14.37	N	5.9	N	-58.94	%
8. Total ECS Weight (ECS weight + ECS fuel weight)	155.27	N	156.9	N	1.05	%

The following table shows that for the conventional ECS the spread is of 26 N, which represents an uncertainty value of 18.4 %. In the case of the electric ECS the spread is of 28 N, which represents an uncertainty value of 19.7 %.

Total ECS Weight (ECS weight + ECS fuel weight)	100%	90%		110%		Spread [N]	Uncertainty [%]
	Value [N]	Value [N]	Difference [%]	Value [N]	Difference [%]		
Conventional ECS	142	129	-9.2	155	9.2	26	18.4
Electric ECS	143	129	-9.8	157	9.9	28	19.7

6.7. Fuel Cost

Taking the results from ELENA and applying the methodology of Prof Dieter Scholz, mentioned in the chapter 2. The following chart has been generated. The number of flights are ranging from 2200 to 3800, which are values considered from 7 to 12 daily flights for the selected mission in the study. The number of days taken from the 365 days in the year is estimated as 320; such estimation was done considered the days which the aircraft is in-operative due maintenance and flight cancellations. Further analysis can be done in future research to estimate more accurately this value.

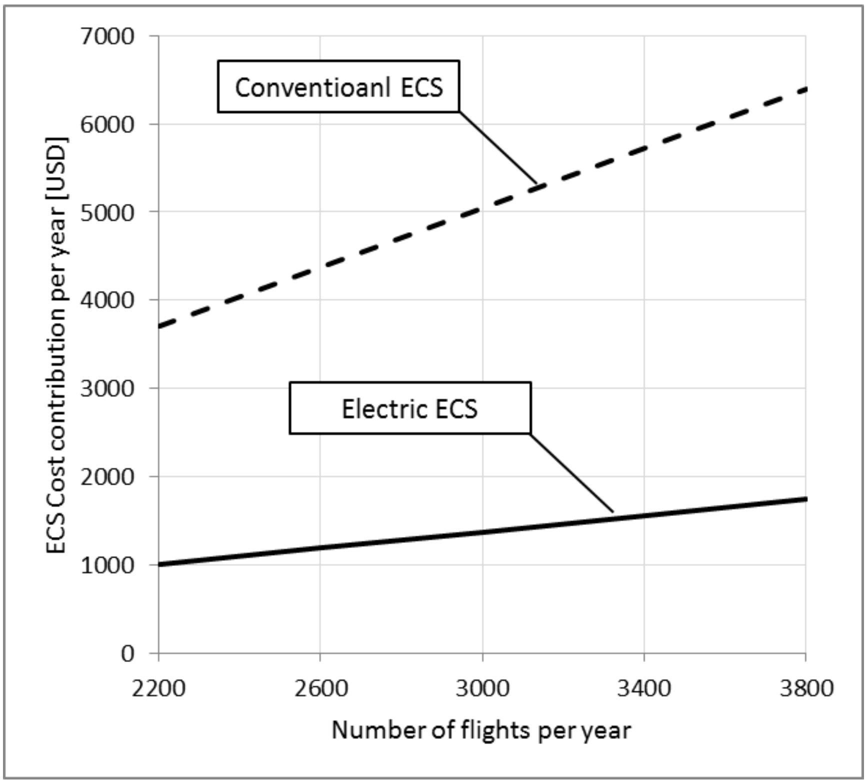


Figure 103: Estimated fuel cost for the electric and conventional ECS's in the Bell 206

CHAPTER 7 | CONCLUSIONS

Generally speaking; the Electric ECS has shown a reduction from 51.2% up to 72.76% for the total fuel penalties. The lower reduction was achieved for the Airbus A321-200. The bigger reduction was achieved for the ATR 72-500 and Bell 206. This considerable reduction for the system has shown that the amount of energy to run a system is considerable bigger when is extracted as pneumatic instead of electric. In the case of the ATR 72-500 and the Bell 206, the benefit has been better due to turboshaft/prop engines lose more net shaft power when power-off take is pneumatic, in comparison with turbojet engines.

This conclusion shows that the energy losses are lower when a thermodynamic process is made by action of the thermoelectric effect, rather than when is made by action of the convection principle.

As seen in the tables, 18, 31 and 44; the average increment on the SFC, due to conventional ECS power extraction was 7.14 %; for the three aircraft object of study. In the case of the Airbus A321-200, this increase was 3.83%. This increment gives a reliable capability to the process used in ELENA, since the real [2]ECS power consumption is ranging from 3 to 5 %. In the case of the Electric ECS, this value average increase of SCF was 1.56%.

A negative contribution that this research has shown is the impact on the system weight, being higher than the conventional system. This result is achieved due to the additional components, mainly the electric motors and compressors. For the case of the extra wiring required to provide electrical power to the Electric ECS, there is not considerable contribution because the lack of pipelines from the engine counteracts with this negative contribution.

In spite of this negative impact produced by an Electric-ECS weight, the improvement in the reduction of the total fuel penalties has been quantitatively better. Therefore, this research shows that the application of an Electric ECS has reached the main goal, towards a reduction on the system energy consumption.

Speaking about reliability in the results and the model ELENA, the overall validation process, presented in the section 3.11, has shown acceptable values through each characteristic that contributes towards the final analysis: the mission profile, ECS conventional power consumption, Electric ECS power consumption, thermodynamic balance, pressurization and fuel penalties.

The use of Simulink® for this study has shown very powerful capabilities to design and simulate the ECS. Among those capabilities, the graphical block diagramming tool and the customizable set of block libraries are the most highlighted characteristics. The graphical block diagramming tool makes the programming easier to understand since each calculation step is built up through diagram connections. On the other hand the block libraries offer a wide range of possibilities to read inputs, interconnect calculations and generate results.

As seen on previous scenarios; for an Air Cycle Machine the cooling requires more bleed air taken from the engine. This fact shows that the cooling process is the major energy consumer.

This research has shown that when configuring a conditioning pack, the most critical parameters that defined the energy consumption were the pressure ratios and the flow amount relations. As seen, when increased the compressor pressure ratio for the ram air, the flow temperature and pressure increased subsequently; becoming more difficult the capacity of the air cycle machine to provide a cold flow. On the other hand, when decreasing this value, the capability to produce enough pressure for the pressurization is reduced.

Aiming to achieve better cabin requirements, the Air Cycle Machine response results can be improved with the implementation of two heat exchangers instead of one. More system weight and electric power consumption must be considered, but it is estimated that the final energy penalties will not be higher than a conventional ECS.

CHAPTER 8 | RECOMMENDATIONS FOR FUTURE WORK

The model is a powerful tool which can be used for further and more detailed analysis through the implementation of more components; such components can include more automatized processes, and more detailed parametric studies.

The automation of processes can improve the data reading for automatic control. As an example; the model can perform a better flow mixture on the manifold section to perform a smoother temperature control into the cabin.

On the other hand a more detailed parametric study can achieve more improvement on the final energy consumption. As seen on the research, the most important parameters to select the configuration for the Electric ECS were the compressor pressure ratio for the ram air, the fan compressor ratio for the cooling flow and the ram-cooling flows ratio. A methodology on a better parametric study at this stage should achieve better parameters which would achieve less electric energy requirement; subsequently, less mass contribution due to smaller electric motors.

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APPENDIX A – PREVIOUS SIMULATION FRAMEWORK

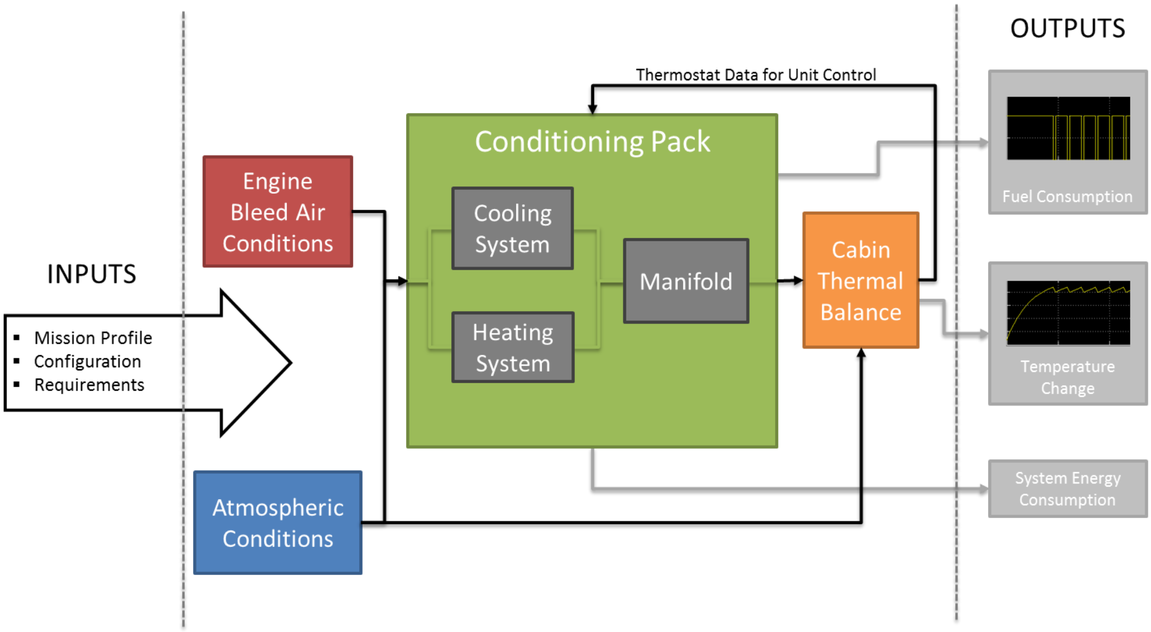


Figure 104: Scheme for the previous version of the analysis model

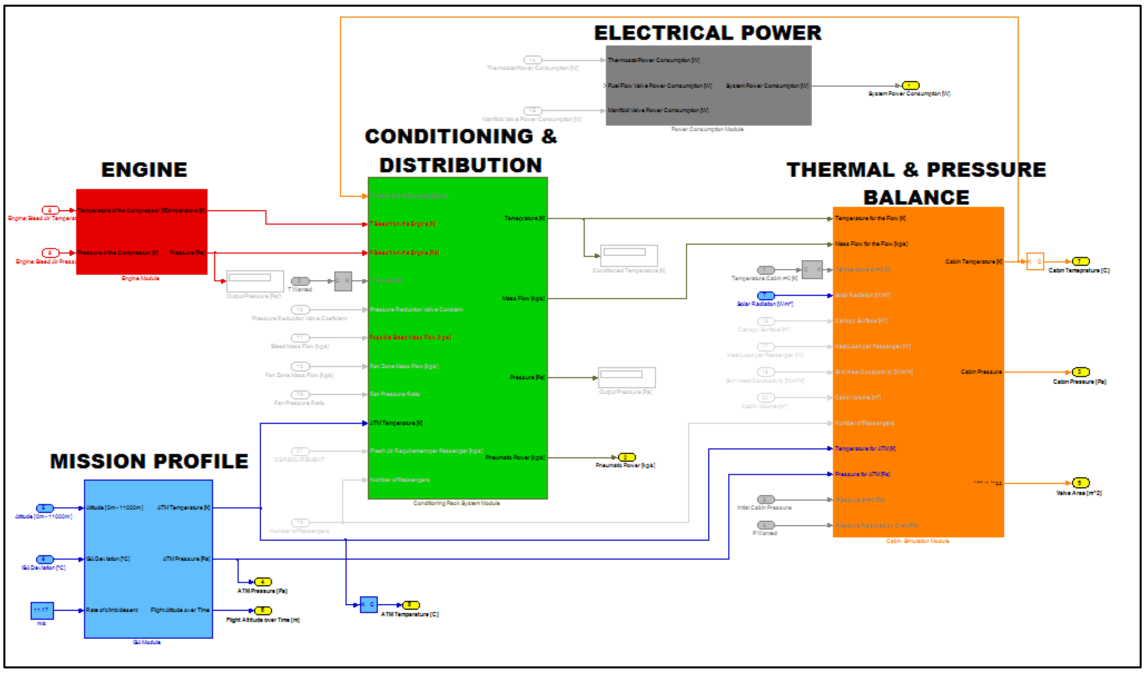


Figure 105: Previous version, built on Simulink ®, of the ECS simulation model

APPENDIX B – ALTERNATIVE METHOD TO CALCULATE THE FUEL PENALTY

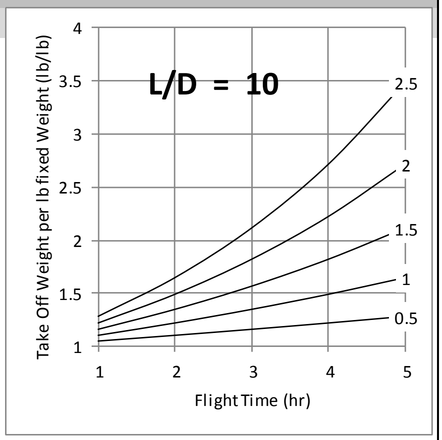
INPUTS			
SFCth	Specific Fuel Consumption for Thrust	1.5	lb/hr-lb
t	Time	1.5	hrs
L/D	Lift/Drag Relation	10	-
g	Gravity	32.17	ft/s^2
Ttb	Turbine Inlet Temperature	2000	R
wb	Bleed Air Flow Rate	0	lb/hr
wr	Ram Air Flow Rate	3600	lb/hr
V	Aircraft Velocity	0	ft/s
Vout	Ram Air Velocity at Outlet	0	ft/s
wv	Expendable Materials (Water)	360	lb/hr
wF	Weight of System	1000	lb
P	Shaft horsepower usage	50	hp
SFCp	Shaft horsepower SFC	0.5	lb/hp-hr

CHARTS

1. Fixed Weight Penalty

wfo 1.252 lb/lb

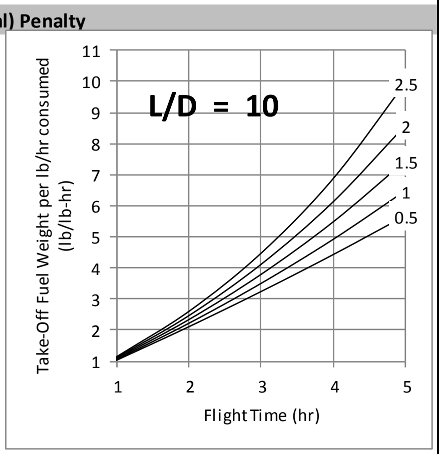
SFC (lb/hr-lb)	1.25	TIME (hrs) 1	2	3	4	5
	0.5	1.051271	1.105171	1.161834	1.221403	1.284025
	1	1.105171	1.221403	1.349859	1.491825	1.648721
	1.5	1.161834	1.349859	1.568312	1.822119	2.117
	2	1.221403	1.491825	1.822119	2.225541	2.718282
	2.5	1.284025	1.648721	2.117	2.718282	3.490343



2. Variable Weight (Expendable Material) Penalty

wv 1.68215 lb/lb-hr

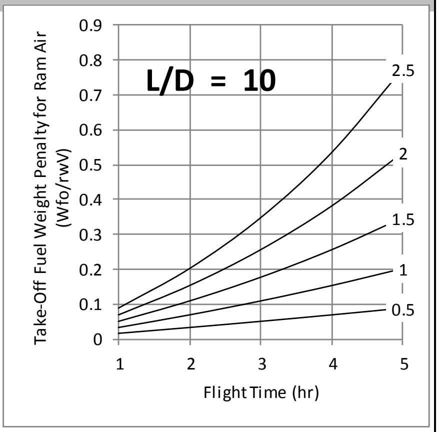
SFC (lb/hr-lb)	1.68	TIME (hrs) 1	2	3	4	5
	0.5	1.025422	2.103418	3.236685	4.428055	5.680508
	1	1.051709	2.214028	3.498588	4.918247	6.487213
	1.5	1.078895	2.332392	3.788748	5.480792	7.446667
	2	1.107014	2.459123	4.110594	6.127705	8.591409
	2.5	1.136102	2.594885	4.468	6.873127	9.961372



3. Ram Air Penalty

wv	0.07843 lb/lb-hr

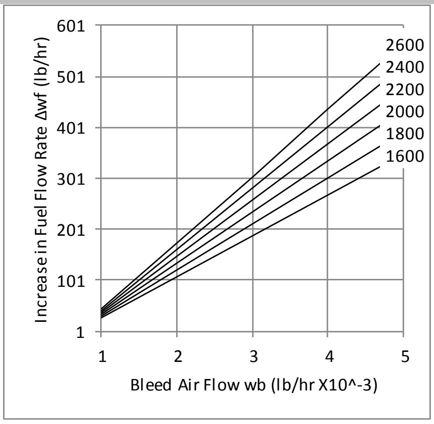
	0.08	TIME (hrs) 1	2	3	4	5
SFC (lb/hr-lb)	0.5	0.015938	0.032692	0.050306	0.068823	0.088289
	1	0.032692	0.068823	0.108753	0.152883	0.201654
	1.5	0.050306	0.108753	0.176659	0.255554	0.347218
	2	0.068823	0.152883	0.255554	0.380958	0.534126
	2.5	0.088289	0.201654	0.347218	0.534126	0.77412



4. Bleed Air Penalty

wv	0 lb/lb-hr
	0.05635

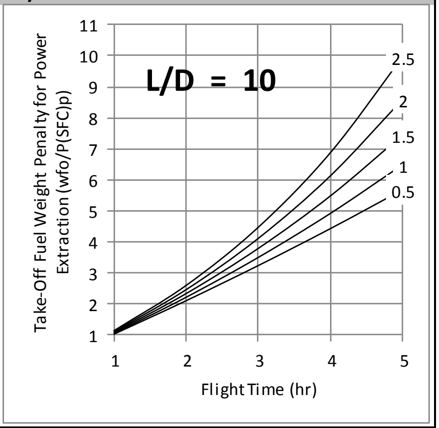
	0.00	Bleed Air Flow 1000	4000	7000	10000	13000
Ttb (R)	1600	26.8	107.2	187.6	268	348.4
	1800	30.15	120.6	211.05	301.5	391.95
	2000	33.5	134	234.5	335	435.5
	2200	36.85	147.4	257.95	368.5	479.05
	2400	40.2	160.8	281.4	402	522.6
	2600	43.55	174.2	304.85	435.5	566.15



5. Shaft Horsepower Extraction Penalty

wv	1.68215 lb/lb-hr

	1.68	TIME (hrs) 1	2	3	4	5
SFC (lb/hr-lb)	0.5	1.025422	2.103418	3.236685	4.428055	5.680508
	1	1.051709	2.214028	3.498588	4.918247	6.487213
	1.5	1.078895	2.332392	3.788748	5.480792	7.446667
	2	1.107014	2.459123	4.110594	6.127705	8.591409
	2.5	1.136102	2.594885	4.468	6.873127	9.961372



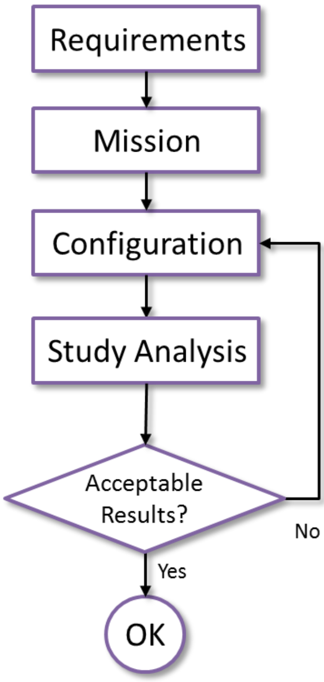
APPENDIX C – PREVIOUR FRAMEWORK PROCESS

Power Consumption
- Thermostat Power Consumption [W]
- Fuel Flow Valve Power Consumption [W]

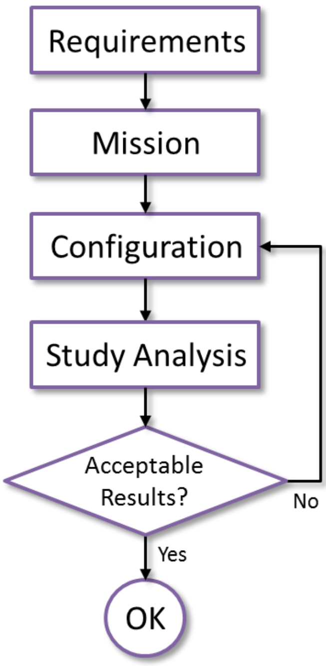
Passenger Issues
- Number of Passengers
- CS29 Air Flow per Passenger [kg/s]
- Heat Load per Passenger [W]

Heating System
- Combustion Efficiency
- Fuel Heating Value [J/kg]

Interior Dimensions
- Canopy Surface [m²]
- Skin Heat Conductivity [W/m²K]
- Cabin Volume [m³]



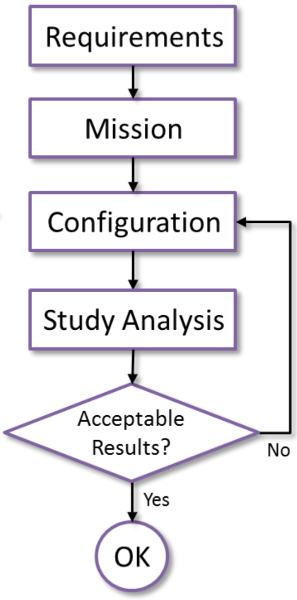
Ambient Conditions
- Solar Radiation [W/m²]
- ISA Deviation [°C]
- Altitude [0m - 11000m]



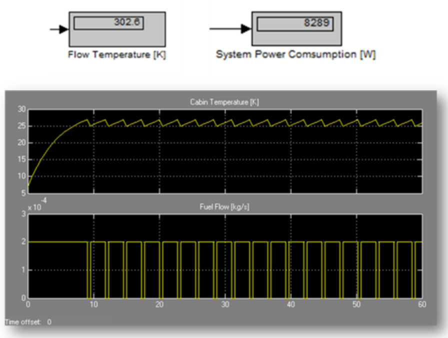
Principal Input/Output
- *Fuel Flow [kg/s]

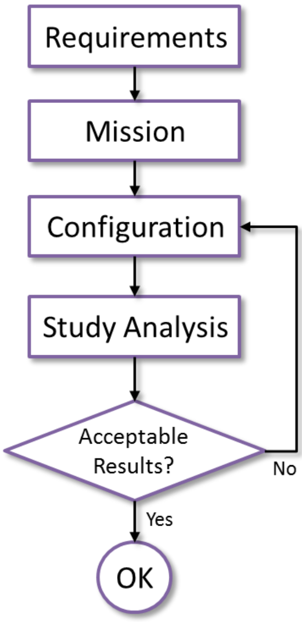
Heating System
- Mass Flow for Cabin [kg/s]
- Mass Flow For Combustion Heating [kg/s]
- Hot Fan Pressure Ratio
- Cold Fan Pressure Ratio

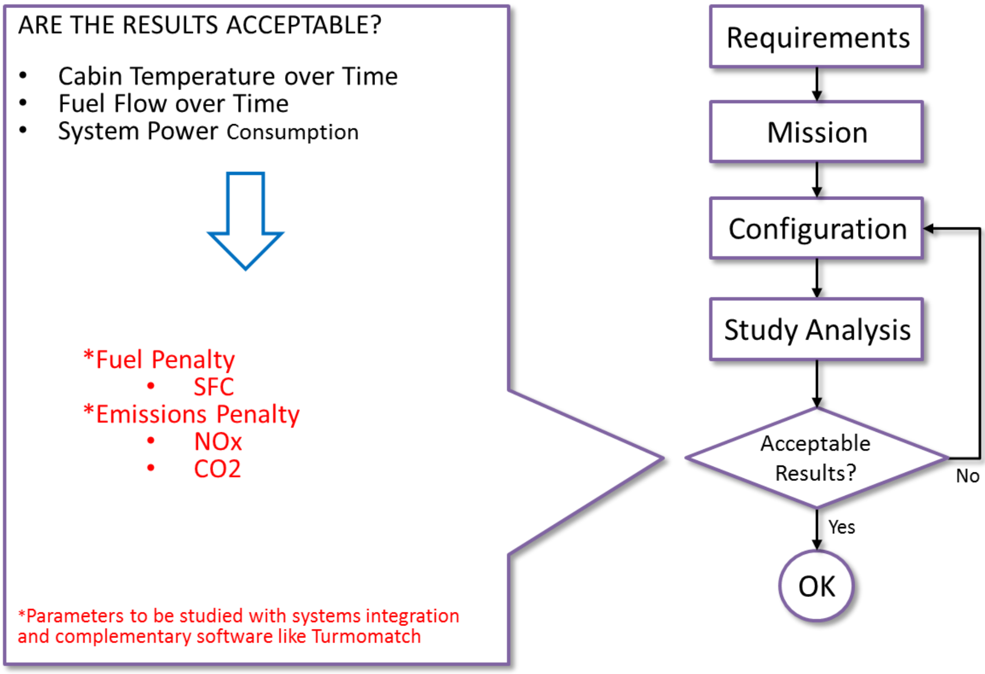
Cabin Conditions
- Temperature Wanted [K]
- Temperature at t=0 [K]
- Heating On/Off



Study:
- Temperature balance in the cabin over time
- Fixed Power Consumed

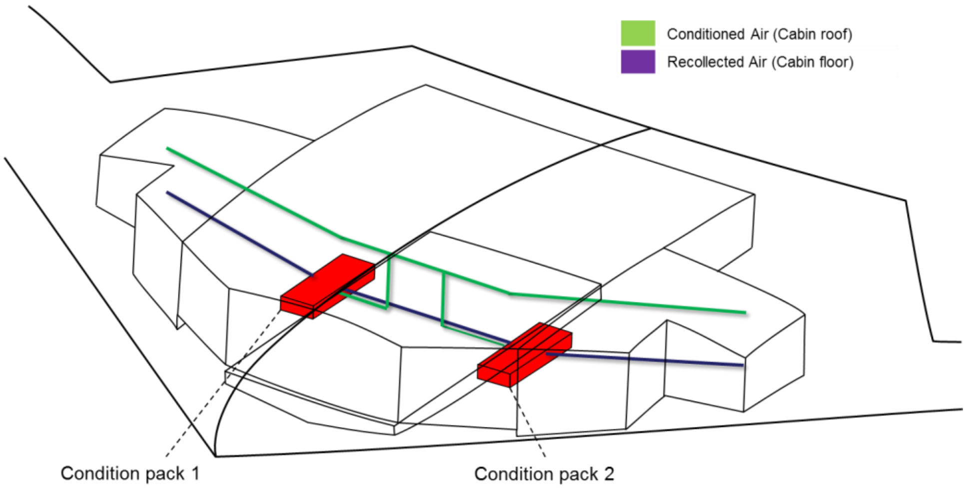


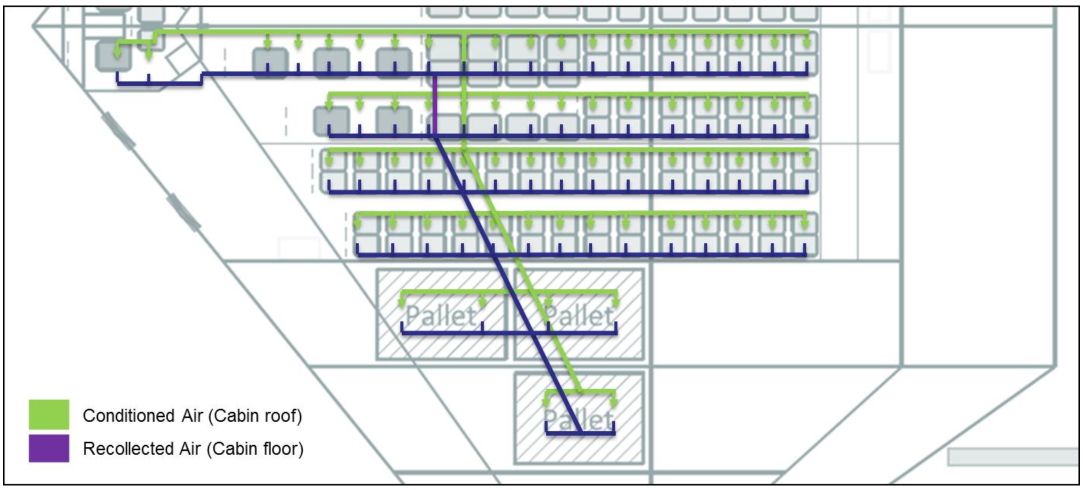


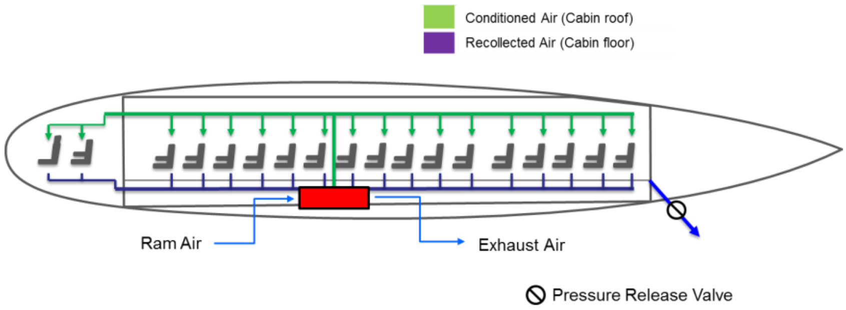

ARE THE RESULTS ACCEPTABLE?
• Cabin Temperature over Time
• Fuel Flow over Time
• System Power Consumption
*Fuel Penalty
• SFC
*Emissions Penalty
• NOx
• CO2
*Parameters to be studied with systems integration and complementary software like Turmomatch
Requirements
Mission
Configuration
Study Analysis
Acceptable Results?
No
Yes
OK

APPENDIX D - CONCEPTUAL ELECTRIC ECS DESIGN FOR A FLYING WING

As part of a contribution for a Group Design Project, an Electric ECS was designed on conceptual stage. The following figures show the results achieved. As seen on the figure the localization of the condition packs, below the main fuselage, letting to locate the intakes for the air which is going to be conditioned.







Components	
Components 	• 2 Conditioning Packs: • 1 inertial water separator • 1 compressor + 1 electric motor • 1 pressure reduction valve • Ozone reduction unit • Air Cycle Machine • Heat exchanger +1 fan + 1 electric motor • 1 centrifugal water separator • 1 manifold mixing unit + 1 control valve • Pipelines • 1 pressure control outflow valve • 2 emergency positive-pressure relief valve • 2 emergency negative-pressure relief valve